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A.W. Wyss, H.K. Willard, and R.M. Evans

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This manual describes the methods, tests, and procedures involved in closing a site to minimize potential environmental hazards. Included is a discussion of the consideration that have been overlooked in abandoned impoundments that have caused real environmental insults. The techniques involved are pertinent to closing an impoundment either by removing the hazardous wastes or by consolidating the waste onsite and securing the site as a landfill. Technical criteria for implementing the closure, specifically those regarding aspects substantially different from a landfill, are given subsequently. Relevant literature or procedures are documented for more in-depth review as necessary.

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CLOSURE OF HAZARDOUS WASTE SURFACE IMPOUNDMENTS

by

A. W. Wyss, H. K. Willard, and R. M. Evans
Acurex Corporation
Energy & Environmental Division
485 Clyde Avenue
Mountain View, California 94042

and

R. J. Schmitt, R. G. Sherman, D. H. Bruehl, and E. M. Greco
Metcalf and Eddy, Inc.
1029 Corporation Way
Palo Alto, California 94303

Contract No. 68-03-2567

Project Officer

John F. Martin
Energy Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land have occurred, giving testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components and waste materials from our industrialized society require a concentrated and integrated attack on the problems.

The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources; for the preservation and treatment of public drinking water supplies; and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication has been developed under a fast tracking activity by the Office of Research and Development for the Office of Solid Waste. Through this activity a series of technical manuals have been prepared to assist in carrying out the current effort to implement the Resource Conservation and Recovery Act.

This manual presents considerations that must be made to develop a plan for closure of surface impoundments containing hazardous wastes. It provides the current engineering judgement on closure operations that minimize the possibility of adverse environmental impacts.

Francis T. Mayo, Director
Municipal Environmental Research Laboratory

PREFACE

The land disposal of hazardous waste is subject to the requirements of Subtitle C of the Resource Conservation and Recovery Act of 1976. This Act requires that the treatment, storage, or disposal of hazardous wastes after November 19, 1980 be carried out in accordance with a permit. The one exception to this rule is that facilities in existence as of November 19, 1980 may continue operations until final administrative disposition is made of the permit application (providing that the facility complies with the Interim Status Standards for disposers of hazardous waste in 40 CFR Part 265). Owners or operators of new facilities must apply for and receive a permit before beginning operation of such a facility.

The Interim Status Standards (40 CFR Part 265) and some of the administrative portions of the Permit Standards (40 CFR Part 264) were published by the Environmental Protection Agency in the Federal Register on May 19, 1980. The Environmental Protection Agency will soon publish technical permit standards in Part 264 for hazardous waste disposal facilities. These regulations will ensure the protection of human health and the environment by requiring evaluations of hazardous waste management facilities in terms of both site-specific factors and the nature of the waste the facility manages. The permit official must review and evaluate permit applications to determine whether the proposed objectives, design, and operation of a land disposal facility will comply with all applicable provisions of the regulations (40 CFR 264).

The Environmental Protection Agency is preparing two types of documents for permit officials responsible for hazardous waste landfills, surface impoundments, and land treatment facilities: Permit Writers Guidance Manuals and Technical Resource Documents. The Permit Writers Guidance Manuals provide guidance for conducting the review and evaluation of a permit application for site-specific control objectives and designs. The Technical Resource Documents support the Permit Writers Guidance Manuals in certain areas (i.e., liners, leachate management, closure, covers, water balance) by describing current technologies and methods for evaluating the performance of the applicant's design. The information and guidance presented in these manuals constitute a suggested approach for review and evaluation based on best engineering judgments. There may be alternative and equivalent methods for conducting the review and evaluation. However, if the results of these methods differ from those of the Environmental Protection Agency method, they may have to be validated by the applicant.

In reviewing and evaluating the permit application, the permit official must make all decisions in a well defined and well documented manner. Once an initial decision is made to issue or deny the permit, the Subtitle C regulations (40 CFR 124.6, 124.7, and 124.8) require preparation of either a statement of basis or a fact sheet that discusses the reasons behind the decision. The statement of basis or fact sheet then becomes part of the permit review process specified in 40 CFR 124.6 through 124.20.

These manuals are intended to assist the permit official in arriving at a logical, well defined, and well documented decision. Checklists and logic flow diagrams are provided throughout the manuals to ensure that necessary factors are considered in the decision process. Technical data are presented to enable the permit official to identify proposed designs that may require more detailed analysis because of a deviation from suggested practices. The technical data are not meant to provide rigid guidelines for arriving at a decision. References are cited throughout the manuals to provide further guidance for the permit official when necessary.

CONTENTS

Foreword iii
Preface iv
Figures viii
Tables viii

1. Introduction 1
   1.1 Purpose 1
   1.2 Content Description 1
   1.3 Related Topics Previously Covered 2
2. General Information on Surface Impoundments 5
   2.1 Characteristics of Surface Impoundments 5
      2.1.1 Definition of Surface Impoundments 5
      2.1.2 Types and Construction of Surface Impoundments . . 5
      2.1.3 Population of Surface Impoundments 6
      2.1.4 Surface Impoundment Uses 6
      2.1.5 Industrial Impoundment Practices 7
   2.2 Methods of Closure 8
      2.2.1 Waste Remains in Place 8
      2.2.2 Waste Removed 9
   2.3 Air and Water Impacts of Surface Impoundments 10
      2.3.1 Surface Water 10
      2.3.2 Ground Water 11
      2.3.3 Air Emissions 12
   2.4 Direct Public Exposure and Site Security 13
3. Environmental Considerations for Closure Plan Analysis 15
   3.1 Leaching Potential of Wastes 15
      3.1.1 Mechanisms of Leaching 15
      3.1.2 Factors Affecting Leaching Rates 16
      3.1.3 Methods to Quantify Leaching Rates 17
   3.2 Containment System Performance 18
      3.2.1 Factors Affecting Performance/Life 18
      3.2.2 Assessment of Liner Condition and Effectiveness . . 21
   3.3 Potential for Waste Migration 23
      3.3.1 Water Balance 23
      3.3.2 Attenuation Mechanisms 27
   3.4 Cover Systems 31
   3.5 Potential for Consolidation of Wastes 35
      3.5.1 Stages of Consolidation 35
      3.5.2 Impacts of Waste Consolidation 36
      3.5.3 Mechanism of Consolidation 36
      3.5.4 Timeframe of Consolidation 38
   3.6 Post-Closure Use of the Surface Impoundment Site 39

CONTENTS (Concluded)

3.6.1 Site Use Limitations for Impoundments Closed as Landfills 41
3.6.2 Site Use Limitations for Impoundments Closed with Hazardous Waste Components Removed 43
3.6.3 Considerations for Limiting Access 44
3.7 Air Emissions 44
3.7.1 Gases Emitted from Impounded Materials 44
3.7.2 Fugitive Dust Emissions 49
4. Technical Criteria for Implementation of Closure Procedures . . 56
4.1 Impoundment Dewatering 58
4.2 Waste Sediment and Soil Removal 59
4.2.1 Wet Methods for Sediment Removal 59
4.2.2 Dry Methods for Sediment Removal 60
4.2.3 Liner Preservation 61
4.2.4 Soil Removal 61
4.3 Sediment Dewatering 61
4.3.1 Passive Dewatering. 62
4.3.2 Active Dewatering 63
4.4 Liner Removal/Repair 64
4.4.1 Reason for Removal 64
4.4.2 Liner Removal Methods 64
4.4.3 Reason for Liner Repair 65
4.4.4 Liner Repair Methods 65
4.5 Soil Contamination Testing 65
4.5.1 Surface Soils 66
4.5.2 Soils Adjacent to Impoundment 66
4.5.3 Soils Remote from Impoundment 66
4.5.4 Drilling and Sampling Programs 67
4.5.5 Ground Water Analysis 67
4.5.6 Soil Analysis 68
4.5.7 Interpretation of Results 68
4.6 Dike Stability 68
4.6.1 Inventory of Historical Information 69
4.6.2 Reconnaissance Investigations 70
4.6.3 Geotechnical Investigations 70
4.6.4 Engineering Criteria 71
4.6.5 Continued Surveillance 73
4.7 Consolidation and Stablilzation of Wastes 73
4.7.1 Consolidation During the Dewatering Process 73
4.7.2 Determination of Consolidation Potential 75
4.7.3 Stabilization of Waste 76
4.8 Control of the Water Balance 78
4.8.1 Need for Control 78
4.8.2 Surface Water Controls 80
4.8.3 Ground Water Controls 81
4.8.4 Leachate Controls 81
4.8.5 Monitoring 81
4.9 Air Emission Control 83
4.9.1 Organic Gas Emission Reduction Procedures 83
4.9.2 Fugitive Dust Abatement 86

FIGURES

Number		Page
3-1	Simplified water balance for open surface impoundment	25
3-2	Moisture distribution during infiltration through an unsaturated soil	27
3-3	Abandoned gravel pit with a clay layer at its base . .	28
3-4	Single aquifer with a deep water table	29
3-5	Breakthrough curve for bulk transport of solutes . . .	30
3-6	Breakthrough curve for bulk transport and diffusion/dispersion	32
3-7	Breakthrough curve with soil-solution interaction . . .	32
3-8	Trace element controls in soils	34
4-1	Surface impoundment closure key steps	57

TABLES

Number		Page
3-1	Liner and Industrial Waste Compatibilities	19
3-2	Types of Soil-Solute Interactions	33
3-3	Sources of Existing Information	40
3-4	Compatibility of Hazardous Waste Impoundment Features and Various Site Uses	42
3-5	Compatibility of Various Site Uses and Impoundment Features After Hazardous Waste Removal	43
3-6	Impounded Waste Gas Generation Rates	46
4-1	Evaporation Potential Variations	71
4-2	Hazardous Waste Consistency Classifications	74

SECTION 1

INTRODUCTION

In line with growing concern for the control of adverse impacts of wastes on our environment, the 94th Congress passed the Resource Conservation and Recovery Act (RCRA) of 1976, PL-94-580, in October 1976. This Act provided for promulgation of "regulations establishing performance standards applicable to owners and operators of facilities for the treatment, storage, or disposal of hazardous wastes... as may be necessary to protect human health and the environment." On May 19, 1980, the Environmental Protection Agency (EPA) promulgated national standards that included closure and post-closure care of such facilities, including surface impoundments (SI's). Manuals describing best engineering judgment criteria for the management of hazardous wastes are necessary to support these regulations.

1.1 PURPOSE

This manual presents a listing of closure plan and post-closure care considerations and details for SI's containing hazardous wastes. It is written primarily for staff members in EPA regional offices or state regulatory offices who are charged with evaluating and approving closure plans for SI's under these regulations. Methods of assessing site closure considerations are documented.

1.2 CONTENT DESCRIPTION

This manual describes and references the methods, tests, and procedures involved in closing a site in such a manner that (a) minimizes the need for further maintenance, and (b) controls, minimizes, or eliminates, to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, hazardous waste constituents, leachate, contaminated rainfall, or waste decomposition products to ground water, surface waters, or the atmosphere. Problems that have been overlooked in abandoned impoundments and have caused environmental degradation are discussed. The techniques involved are pertinent to closing an impoundment either by removing the hazardous wastes or by consolidating the waste onsite and securing the site as a landfill. Technical criteria for implementing the closure, specifically those regarding aspects substantially different from a landfill, are given. Relevant literature or procedures are documented for more in-depth review as necessary.

1.3 RELATED TOPICS PREVIOUSLY COVERED

A large and useful group of support documents has been prepared by the EPA that relates to SI closure plans. The basic manuals of concern to those regulating the closure of impoundments are identified below as technical resource documents. Other documents that further explain the subject technical points are referenced in the appropriate sections of this manual. Eight technical resource documents have been developed for support of the recent RCRA rules. Since these documents will be published together, they will be readily available to supplement one another. They include this manual plus the following:

- "Landfill and Surface Impoundment Performance Evaluation"[1]
- "Evaluating Cover Systems for Solid and Hazardous Waste"[2]
- "Guide to the Disposal of Chemically Stabilized and Solidified Wastes"[3]
- "Hydrologic Simulation on Solid Waste Disposal Sites"[4]
- "Management of Hazardous Waste Leachate"[5]
- "Lining of Waste Impoundment and Disposal Facilities"[6]
- "Design and Management of Hazardous Waste Land Treatment Facilities"[7]

The "Landfill and Surface Impoundment Performance Evaluation" manual is intended to provide guidance in evaluating designs to predict the movement of liquids through and out of an SI. It includes a discussion of acceptable operating procedures, design configurations, analysis procedures, and techniques for interpretation of results as they apply to impacts on ground and surface water.

The manual "Evaluating Cover Systems for Solid and Hazardous Waste" is intended for use by the regional offices in their evaluation of applications from owners/operators of solid and hazardous waste disposal areas. More specifically, it is a guide for evaluation of closure covers on solid and hazardous wastes. The manual provides a guide to the examination of soil, topographical, and climatological data, closure cover evaluation recommendations, and a discussions of post-closure plans.

The "Guide to the Disposal of Chemically Stabilized and Solidified Wastes" provides guidance to waste generators and regulatory officials in the use of chemical stabilization/solidification techniques for limiting hazards posed by toxic wastes in the environment. The current state and performance of hazardous waste disposal and long-term storage techniques are discussed. In addition to a discussion of major chemical and physical properties of treated wastes, a list of major stabilization/solidification technology suppliers and a summary of each process are provided.

The document "Hydrologic Simulation on Solid Waste Disposal Sites" presents an interactive computer program for simulating the hydrologic characteristics of a solid hazardous waste disposal site operation. Using minimal input data from the user, the model will simulate daily, monthly, and annual runoff, deep percolation, temperature, soil-water, and evapotranspiration. The manual provides sufficient information and commands so that an inexperienced user may perform the operation. The model is designed for conversational use, that is, interaction with the computer is direct and output is received immediately.

The manual "Management of Hazardous Waste Leachate" presents management options that a permit writer or hazardous waste landfill operator may consider in controlling a leaching problem. The manual contains the following: a general discussion of leachate generation; a section on leachate composition providing the permit writer with possible guidelires for determining the relative hazard of a particular leachate; a discussion of five potential management options for the off-site treatment of leachate or the on-site treatment of hazardous waste; and a discussion of treatment technologies that, on a laboratory scale, have demonstrated reasonable success in treating leachate.

"Lining of Waste Impoundment and Disposal Facilities" provides information on performance, selection, and installation of specific liners and cover materials for specific disposal situations, based upon the current state of the art of liner technology and other pertinent technology. It contains descriptions of wastes and their effects on linings; a full description of various natural and artificial liners; liner service life and failure mechanisms; installation problems and requirements of liner types; costs of liners and installation; and tests that are necessary for preinstallation and monitoring surveys.

The document entitled "The Design and Management of Hazardous Waste Land Treatment Facilities" presents a dynamic design approach for land treatment facilities. This design strategy is based upon sound environmental considerations and is structured into a total system approach. The manual discusses site assessment procedures aimed at selecting acceptable locations. This site assessment procedure consists of (1) technical consideration of site characteristics and (2) sociographical considerations of area land use. In addition, the manual describes specific land treatment components and explains why they are important to an effective design. These components include: the land treatment medium, hazardous waste streams, preliminary tests and pilot experiments on waste-soil interactions, facility design and management, monitoring, changing wastes, contingency planning, and site closure.

REFERENCES FOR SECTION 1

1. Moore, C. A., "Landfill and Surface Impoundment Performance Evaluation," U.S. Environmental Protection Agency, SW-869.

2. Lutton, R. J., "Evaluation Cover Systems for Solid and Hazardous Waste," U.S. Environmental Protection Agency, SW-867.

3. Malone, P. G., L. W. Jones, and R. J. Larson, "Guide to the Disposal of Chemically Stabilized and Solidified Wastes," U.S. Environmental Protection, Agency, SW-872.

4. Perrier, E. R. and A. C. Gibson, "Hydrologic Simulation of Solid Waste Disposal Sites," U.S. Environmental Protection Agency, SW-868.

5. Monsanto Research Corporation, "Management of Hazardous Waste Leachate," U.S. Environmental Protection Agency, SW-872.

6. Matrecon, Inc., "Lining of Waste Impoundment and Disposal Sites," U.S. Environmental Protection Agency, SW-870.

7. K. W. Brown & Associates, Inc., "Design and Management of Hazardous Waste Land Treatment Facilities," U.S. Environmental Protection Agency, SW-874.

SECTION 2

GENERAL INFORMATION ON SURFACE IMPOUNDMENTS

2.1 CHARACTERISTICS OF SURFACE IMPOUNDMENTS

2.1.1 Definition of Surface Impoundments

"Surface impoundment" or "impoundment" means a facility or part of a facility that is a natural topographic depression, manmade excavation, or diked area formed primarily of earthen materials designed to hold an accumulation of liquid wastes or wastes containing free liquids. An impoundment is not an injection well and may be lined with manmade materials. Examples of SI's are holding, storage, settling, and aeration pits, ponds, and lagoons.

Exceptions to the above definition include concrete-lined basins, which are, by definition, considered tanks. Tanks are stationary devices designed to contain an accumulation of hazardous waste. They are constructed primarily of nonearthen materials (e.g., wood, concrete, steel or plastic) that provide structural support.

2.1.2 Types and Construction of Surface Impoundments

SI's may be natural or manmade depressions lined or unlined and may range in area from a few tenths of an acre to hundreds of acres. Manmade impoundments range in depth from 2 to 3 feet to as much as 30 feet or more below the land surface.[1] Impoundments are generally built above the naturally occurring water table, and some may be constructed on the land surface by using dikes or revetments. Sometimes diked impoundments are designed to take advantage of natural topographical features such that valleys or natural depressions are diked on one or more sides with the naturally occurring slopes forming the remaining sides of the containment area. Dikes may also be required for impoundments in areas of high water tables or to take advantage of impermeable surface soils.

Impoundments may be operated individually or interconnected so that the flow moves from one impoundment to another in series or parallel. Many impoundments discharge, either continuously or periodically, while others lose their fluids by evaporation or infiltration into the soil. Impoundments may be unlined, permitting seepage of fluids into the soil for the purpose of percolation or infiltration. For certain wastes, impoundments are lined to prevent any seepage of fluid. Typical liner materials include clay, concrete, asphalt, soil sealants, and synthetic membranes. The actual type and construction characteristics of an SI depend on many factors, including such site-specific ones as:

- Physical properties and chemical composition of the wastes
- Soil permeability, and geological and geochemical characteristics of the local and surrounding soil
- Depth to the water table
- Rates of precipitation and evaporation (meteorology)

2.1.3 Population of Surface Impoundments

Existing inventory information for SI's containing hazardous wastes is scant and inconsistant. A general survey estimated that there are nearly 133,000 SI sites in the U.S.; 75 percent are industrial waste sites, 15 percent are agricultural, and 10 percent are municipal, institutional, and private/commercial (domestic or sanitary).[1] This survey includes surface impoundments regardless of the waste type; therefore municipal, industrial, and agricultural wastewater treatment facilities are included in the quantitative information. The highest numbers of industrial impoundments are as follows: oil and gas extraction industry, 71,832; agriculture (crops and livestock) 19,363; and bituminous coal mining, 14,170.

In 1979, EPA estimates indicated that there were 96,800 SI sites with a total of 160,000 individual impoundments.[2] More recent EPA data (August 1980) indicate that there are at least 26,000 industrial impoundments (pits, ponds, and lagoons) covering 430,000 acres currently in use.[3] The majority of SI's are in the oil and gas extraction and mining industries, while the largest impoundments are in the mining, paper and pulp, and electrical utility industries.

2.1.4 Surface Impoundment Uses

SI's can be used for temporary holding of discharged wastes or spills or for long-term dewatering. A very common impoundment is a settling pond for separation of suspended solids from liquids. Chemical additives can be introduced to accelerate solids coagulation and precipitation. A number of existing SI's used as settling ponds are periodically dredged to restore them to their original capacity.

Some impoundments are designed specifically to permit seepage of fluids into underlying aquifers. These impoundments are unlined and situated on permeable soils. Others are designed to prevent seepage and to serve as temporary or permanent holding or evaporation impoundments. Disposal of waste in these nondischarging impoundments is accomplished by a combination of evaporation and infiltration. Evaporation is most effective in the arid parts of the western states where climatic conditions favor losses by this mechanism.

2.1.5 Industrial Impoundment Practices

Industrial wastes are highly variable in composition and flow, hence, industry employs a wide variety of practices in treating and disposing these fluids and sludges. Impoundments are used for the aeration, oxidation, stabilization, settling, disposal, and storage of wastes.

Mining and milling operations produce various wastewaters such as acid mine water, solvent wastes from solution mining, and wastes from dump leaching. Waste streams may be treated and the resulting sludges stored in impoundments. Settling for the separation, washing, and sorting of mineral products from tailings and the concentration and recovery of valuable metals (e.g., copper by precipitation) can be carried out in impoundments.

The oil and gas industry is one of the largest users of SI's. Fluids contained in these impoundments consist of salt water associated with oil extraction and deep-well repressurizing operations, oil-water and gas-fluids to be separated or stored during emergency conditions, and drill cuttings and drilling mud. In many cases, these intermittent or continuously produced wastes are treated in steel tanks or concrete basins with either the residuals or the treated wastewater disposed via large earthen evaporation ponds.

Impoundments found in the textile and leather industries are primarily used for wastewater treatment and sludge disposal. Textile sludges may contain dye carriers such as halogenated hydrocarbons and phenols. Heavy metals such as chromium, zinc, and copper may also be present. Leather tanning and finishing wastes and wastewater sludges contain chromium, sulfides, and nitrogenous compounds.

The chemical and allied products industry produces literally thousands of products and many different waste streams. Waste stream processing may involve the use of impoundments for wastewater treatment, sludge disposal, and residuals treatment and storage. Impounded waste constituents also vary considerably and are related to the product produced, feedstock used, and the production method employed. In the case of agricultural chemicals (i.e., fertilizers and pesticides), potential impounded wastes from phosphate fertilizer production will contain phosphorous, fluoride, and nitrogen where ammonia is used as a basic raw material. Also associated with the manufacture of phosphate fertilizers are trace elements that may be extracted and discarded in the waste stream such as cadmium, which is found in impounded gypsum wastes.

Other examples of industrial SI uses that may result in the treatment, storage, or disposal of hazardous wastes can be found in petroleum refining, primary metals production, wood treating, and metal finishing. Impoundments are also used for air pollution scrubber sludge and dredging spoils disposal.

2.2 METHODS OF CLOSURE

The objective of implementing proper SI closure procedures is to control, minimize, or eliminate adverse environmental and human health impacts. This objective is accomplished only if the impoundment sites have been adequately designed and constructed to contain hazardous wastes on a long-term basis. SI's are generally constructed as temporary containment structures designed for variable lengths of service life.

To alleviate adverse environmental impacts, SI closure plans must address either of two means of SI closure. These are closure plans where the hazardous wastes and hazardous waste residuals (including liners, soils, and equipment contaminated with hazardous wastes) are either left to remain in the impoundment after closure or removed from the impoundment site.

2.2.1 Waste Remains in Place

If hazardous wastes are to remain in the impoundment, the closure plan must include the implementation of procedures that will: (1) prevent migration of waste from the impoundment via ground water, surface water, and air, (2) control surface water infiltration, and (3) prevent erosion after closure. The remaining wastes should not contain free liquids and the closure plan must meet, as a minimum, the same requirements as those for landfills. Beyond these requirements, considerable flexibility is allowed in the final plan so that site-specific characteristics can be considered. The following factors must be considered in developing closure plans when an SI is closed as a landfill:

- Type of waste and waste constituents in the impoundment
- The characteristics of the waste and waste constituents including mobility, leachability, reactions, degradation, and byproducts
- Potential intended use of the closed SI
- Site location and topography with respect to the potential impact caused by pollutant migration; for example, proximity to population centers, ground water, surface water, drinking water sources, soil permeability, depth of watertable, and geological and geochemical characteristics of surrounding soil
- Climate including amount, frequency, and pH of precipitation
- Cover material and its characteristics, such as porosity, permeability, thickness, and final slope
- Water balance control measures
- Amount and type of vegetation

In addition to reducing the free liquids from SI's, other waste preparatory procedures may be necessary prior to the construction of a landfill cover. These procedures may consolidate and stabilize the wastes so that the potential for leaching and differential settlement are minimized. Such procedures are reviewed in Section 4.

2.2.2 Waste Removed

In some cases of SI closure, it may be necessary or advantageous to remove the wastes and waste residuals. Instances where this may be required include:

- SI's with irrepairable liners containing wastes with a high potential for the generation of toxic leachate
- Impoundments with dikes in poor condition that may require extensive and costly repair
- Cases where the type of waste or waste constituents generate gases that cannot be controlled adequately or economically
- Sites where planned end uses require the least possible contamination
- Impoundments where free liquids cannot be removed to yield consolidated wastes of sufficient density to support the cover and associated construction vehicles

Closure of SI's by removing wastes would be typical for those impoundments that are periodically dredged, as in the case of settling or evaporation ponds. It should be noted, however, that contaminated liners and underlying soils may also have to be removed. Such soil, particularly the highly contaminated portions, could present a significant future danger to public health and the environment if left in place. Movement of water through the soil could cause leaching of contaminants and potential ground water or surface water contamination. Therefore, the underlying soil must be quantitatively analyzed for the hazardous constituents of the impounded wastes. The dredged or excavated wastes and contaminated waste residuals from an SI would need to undergo removal, transport, and disposal methods that meet the regulations and procedures established for hazardous materials. This will ensure that waste and waste residual can be removed without significant environmental risk.

Upon removal of hazardous wastes and waste residuals, the impoundment site itself may require some degree of reclamation. This may be necessary for the following reasons:

- Erosion control
- Surface runoff control
- Water table restoration

- Post-closure usage
- Dust control

Site reclamation may include filling an impoundment with native soils or leveling the dikes to provide a graded elevation consistent with the surrounding area. The nature and extent of site reclamation after hazardous wastes have been removed is dependent on local or regional regulations and site-specific factors.

In summary, specific SI closure procedures are quite varied and dependent on individual site characteristics. This allows an owner or operator the opportunity to present, in a closure plan, those procedures that will prevent or minimize the migration of waste from the impoundment after closure. Each facility needs to be considered on a case-by-case basis. Details of the controls and effects of items mentioned in this section are given in Section 4.

2.3 WATER AND AIR IMPACTS OF SURFACE IMPOUNDMENTS

The adverse water and air impacts that can result from improperly closed SI's are quite evident but frequently overlooked. Specific cases of pollution of surface and ground waters or unhealthy ambient air have been reported.[4]

2.3.1 Surface Water

Public exposure to hazardous wastes contained in SI's can be quite sudden and uncontrollable when dikes are breached or lagoons are washed out during high surface runoff periods. General public awareness of impoundment hazards has been heightened by news media reports of dike failures or waste slurry pond spillage during heavy runoff. Most surface water contamination occurs from impoundments where the waste containment system was unable to adequately handle short-term unexpected events.

As explained in Section 2.1, SI's have an extremely wide variety of uses and wastes. A pond's size or prominence often determines the attention its closure and use are given by owners and regulatory authorities. Copper tailings ponds in Arizona that are over 1 mile long and 100 feet high might be closely observed and monitored. Such ponds are used for long periods of time accepting slurry tailings for settling of the solids and evaporation or decantation of the fluids. Seepage of impounded fluids into ground water below the pond bottom or through a diked area can be anticipated. Conversely, small onsite sludge disposal sites can be randomly used and easily overlooked or neglected. Such impoundments have caused a large fraction of the surface water contamination cited previously.

Although such inundations are apparent and alarming, equal concern is merited for leached contaminants. A well engineered (as detailed in references 5, 6, and 7) containment system is essential for public safety, since liners and even fixed sludges can leak over a period of time.

2.3.2 Ground Water

Contamination of underground waters from improperly closed SI's most directly exposes the local population through well water withdrawals. Exposure can also occur as a result of contaminated ground water seepage into basements and subsequent volatilization of dissolved constituents. Underground contamination of water can cover large areas traveling rapidly of to 2 feet per day, although average rates are somewhat less.[8] Case history studies generally show that water in shallow unconfined aquifers is the first to be contaminated by seepage of wastes from impoundments. Such contaminated waters may remain localized or extend considerable distances.[1] Concerned over public safety relating to the problem of seepage of wastes from impoundments, the EPA initiated an assessment program to rate the contamination potential of ground water from SI's and to develop practices for their evaluation. A method of determining "potential endangerment" to current water supplies as a function of waste and subsurface water characteristics has been reported.[8] This report developed an evaluation system based on ratings for:

- Ground water availability
- Ground water quality
- Waste hazard potential (determined by waste source or industry or chemical content)
- Earth material characteristics (unsaturated zone beneath the impoundment)
- Proximity to ground or surface source of drinking water

While this system provides methods for evaluating ground water contamination potential from impoundment waste seepage, life characteristics of the waste containment system must also be evaluated.

Most general literature does not present useful data for realistic containment system life predictions. This is especially true for liner waste compatibility where the wastes are industrial sludges (e.g., electroplating, oily refinery, acid steel pickling, toxic pharmaceutical, and related wastes). To contain these types of materials, the liner must resist attack from chemicals (solvent, oils, greases), ozone, ultraviolet radiation, soil bacteria, mold, fungus, and even vegetation.[9] Weather resistance is necessary to withstand stresses associated with wetting-drying, freezing-thawing, or earth shifts at the site. They also must resist laceration or puncture from cleaning or operating equipment or matter found in the fluids or sludges contained. In impoundments with consolidated or fixed contents, the potential for public exposure to hazardous materials may be reduced but is not totally eliminated.

Comparative tests have been made on a variety of sludges using long-term leaching or elutriation to determine the release of pollutants from sludges that had been consolidated or untreated.[10] Waste sludges from electroplating, chlorine production, inorganic pigment production, flue gas desulfurization, and other industrial wastes were fixed with a variety of additives and still exhibited high metal and organic constituent losses under some leaching conditions.

Such elutriate tests do not simulate a disposal site since no provisions are made for modeling the attenuation of pollutants by soil nor their dilution by site ground water. But these tests are rapid and techniques are simple for comparing the degree of fixation for sludges on the basis of pollutant migration from the sludge to the elutriate. One use of these elutriate tests is to compare the leaching of fixed and raw sludge under similar conditions. Although by fixing a sludge it may become more highly consolidated, the hazardous components may leach out at the same rate as without fixing. Results of one elutriate study showed that metals were leached as rapidly from chemically stabilized sludges as raw sludge.[10]

Although chemical fixation may provide only limited added control against leaching,[10] this procedure usually greatly controls the rate of air emissions or surface losses of chemical constituents.

2.3.3 Air Emissions

When SI sites become inactive but remain unclosed, liquid waste may volatilize organic compounds (e.g., benzene, chloroform, chlorinated ethylenes) while bacterial activity and algal growth on sludges and liquid wastes can produce gases. Such vapors and gases may be objectionable (odorous) and unsafe (toxic gases).

Public exposure to materials thought to be safely contained is occurring through air emissions at many locations. A typical example is emissions of PCB in New York from contaminated material removed from direct water contact but stored without adequate control of vapors. Annual losses of PCB to the air from dredge spoil sites within the Hudson River Basin were reported at 205 lb/year, while ground water transport was less than 1 lb/year.[11] Erosion and physical removal at the same sites accounted for losses of about 90 lb/year.

A well recognized characteristic of poorly closed waste impoundments is the bare surface that often gives rise to excessive dust during winds or vehicle use. Air emissions, such as decomposition gases, organic vapors, and odors, affect more than aesthetics especially during subsequent site use. Decomposition gases (e.g., hydrogen sulfide, methane, and carbon dioxide) and organic vapors can diffuse upward affecting surface covers (killing grass and plants, and bubbling up impermeable membranes) and buildings (due to subsequent consolidation and settlement and toxic gas accumulation).

Volatilization of organic wastes from open or abandoned SI's involve three different processes: (1) direct vaporization of the organic liquid or mixtures, (2) volatilization of liquid chemical wastes from water, and (3) volatilization of organics that have adsorbed onto soil or other solid material. Decomposition gas formation is dependent on site temperature, organic waste character, lack of oxygen, and bactericidal constituents (high pH and heavy metals).

2.4 DIRECT PUBLIC EXPOSURE AND SITE SECURITY

Hazardous materials that leach, diffuse, or are otherwise conveyed out of a treatment, storage, or disposal site can and have caused public health and environmental problems. Although environmental degradation from impoundment pollution may not seem as hazardous as from landfills, typical incidents confirm the severity of potential public exposure. In addition to emissions listed here, direct contact of wastes at inactive but unclosed sites frequently occurs. Abandoned coal cleaning and industrial sludge holding sites that still contain contaminated runoff have been cited as a public nuisance.[1,12] Such impoundments are both a physical safety hazard and potential exposure hazard to an unsuspecting site user. Wind blown eroded waste from dry impoundment surfaces and foam and aerosols from saturated and inundated wastes can be carried considerable distance, thereby extending the range of public exposure to abandoned hazardous waste impoundments.

An integral part of site maintenance is security against uncontrolled access by the public. Improperly closed impoundment sites have had dikes breached, unauthorized public dumping, rifle target practice ranges set up on them, and unofficial testing grounds developed for offroad motorcycles and four-wheel drive vehicles.[12]

Of utmost concern for site security is the preservation of hazardous waste containment systems. Surface water diversion and cover systems may rapidly deteriorate if disruptive surface activity and soil removal occurs during unplanned site use. Fencing, policing, and site rezoning are necessary site closure activities that can help preserve containment systems. These are discussed in Section 3.

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SECTION 3

ENVIRONMENTAL CONSIDERATIONS FOR CLOSURE PLAN ANALYSIS

This section discusses environmental considerations that should be addressed in a plan for SI closure. The closure of new and existing impoundments by dewatering and residual solids removal or in situ stabilization is also covered.

3.1 LEACHING POTENTIAL OF WASTES

Solids in impoundments may be leached by liquid added to the impoundment by precipitation, by fluids already present in the waste, or by other flowing or infiltrating fluids. If the impoundment is unlined or the liner is breached and if an overflow from the impoundment occurs, leachate can seep into the adjacent soil and eventually into ground water. This is of special concern if the wastes contain hazardous materials. Mechanisms releasing the waste constituents to the eluant are not fully characterized, and the methods to quantify leaching rates are not well established. But a discussion of these factors is certainly warranted, as considerable information exists from specific cases of leaching.

Most of the current information on waste leaching was developed from landfills holding either municipal or industrial waste. Even laboratory studies have either selected actual leachate from such systems[1,2] or set up conditions to duplicate them.[3,4] Leaching of materials from uncovered impoundments is generally considered to more closely follow the release of materials in pond or lake sediments for which a very large amount of descriptive data exist. This similarity is closest for lake sediments exposed to ground water seepage.[5,6]

3.1.1 Mechanisms of Leaching

When the leaching fluid (e.g., water) is absorbed into or passes through a waste or impoundment sediment, various physical and chemical factors affect the rate and extent to which contaminants in the waste diffuse into the liquid medium. Leaching mechanisms and factors affecting these mechanisms are fairly well established for certain specific nutrients used in agriculture and forestry. These simplified systems have been examined for many types of soil and moisture conditions.[7,8] Unfortunately, these results are only poorly analogous to multiple constituent wastes. Many attempts have been made to model the processes involved for complex wastes, but the actual mechanisms are so complex in nature that these models, though quantitative in principle, serve only as qualitative guides.

One approach is to model the transport as an equilibrium phenomenon (i.e., to assume that the driving forces for transport, the activity, coefficients, and concentrations of all species are balanced among the solid, liquid, and gaseous phases of the waste impoundment).[9,10,11] Under these conditions, liquids remain in contact with the waste long enough for chemical exchange to attain equilibrium. Such an equilibrium model serves as a worst case for concentration of contaminants in the leaching medium. Even such a simple model in concept is difficult to apply in reality because of the complex task of identifying and establishing the various equilibria involved.

A more elaborate approach is based on transport and mixing (convective transport, diffusion, and gravitational transport) and the kinetics of dissolution reactions as well as the kinetics of any chemical reactions involved.[11] A further extension is to consider biological activity.[11] Such an approach is not simple, thus, empirical tests and factors affecting leaching are discussed below.

3.1.2 Factors Affecting Leaching Rates

The character and composition of leachate depends on the composition of the waste material and environmental factors (e.g., meteorological conditions).[11,12] Factors that exert a strong influence on the leaching potential include:

- Chemical composition
- pH of the waste and eluant
- Oxidation and reduction conditions
- Buffer capacity
- Complexation capacity for organic compounds and metals
- Ionic strength
- Dielectric constant
- Temperature

Factors that primarily affect leachate transport include:

- Flowrate of eluant
- Specific surface area of waste material
- Porosity
- Permeability

The effects of these factors have been discussed in detail by Lowenbach.[11] Laboratory test data on a specific waste and site can be generated for these parameters, and various leaching models can be applied.

Finally, meteorological conditions should be factored in. Precipitation has a direct bearing on the quantity and flowrate of leaching water and, hence, eluant. The distribution of precipitation with respect to time is also significant. Several investigators have shown that liquid in contact with metal bearing coal wastes contain constituents whose concentration is directly related to the time of contact with the waste.[13,14] They reported that the concentration of contaminants in the leachate initially increased significantly with new precipitation but then decreased as existing fluid was replaced by new liquid.

3.1.3 Methods to Quantify Leaching Rates

To assess the leaching potential of wastes and, hence, aid in evaluating alternative SI closure plans, it is desirable to have quantitative, standardized tests. These tests should be representative of the actual impoundment situation, reproducible, conservative (worst case approach), and capable of generating meaningful test data. They need to be standardized for comparison of results and for comparison of the leaching potentials of different wastes.[1] Leaching tests fall into three categories: (1) batch (shake) tests, (2) column tests, and (3) field cell tests.[11] Shake tests involve placing a sample of the waste material to be leached in a container with an appropriate eluant, agitating the mixture for a specified period of time, and analyzing the resulting leachate. This technique is a simple and rapid method of generating a variety of equilibrium and kinetic data. However, the technique is crude as conditions may not be representative or approximate those of the actual environmental conditions. Column tests, involving flow of the eluant through a column packed with the waste, may be a better simulation of waste and liquid contact in an actual situation. The major disadvantage is the great length of time needed to yield meaningful data, usually months to years. Finally, actual field test sampling is even better, though test conditions would be difficult to control and testing would involve great expense and time. In fact, sampling and handling procedures are critical and elaborate.[15] Current research emphasis is on the batch or shake test. EPA has sponsored a study to compile and evaluate the various leaching methods now available. Unfortunately, no single existing leachate test fulfills all the desired needs.[11]

Over 30 shake tests were evaluated and compared by Lowenbach.[11] The study identified three shake tests for further investigation: the IU Conversion Systems test,[16] the State of Minnesota test,[17] and the University of Wisconsin test.[18] A subsequent EPA program investigated these three tests further, and concluded the Wisconsin test was the only test able to representatively leach each of 14 different industrial wastes supplied by EPA, and also was the procedure with the most aggressive conditions.

In addition to data from specific leaching tests, information on site soil and water balance characteristics must be compiled. These data may be utilized to evaluate potential contamination by a method described by Silka and Swearingen.[19] By developing a rating for the (1) waste hazard potential, (2) ground water availability and quality, (3) soil zone, and (4) proximity of water supplies, a net potential for drinking water contamination from leaching can be determined. The latter three ratings must be determined for specific sites as described in reference 19 or Section 3.3, Potential for Waste Migration, of this manual. Waste hazard potential can be determined by waste specific leaching tests or from general references.

The movement or attenuation of leached waste constituents and the influence of various soil characteristics has been researched and reported[20,21,22] and is discussed in Section 3.3.

3.2 CONTAINMENT SYSTEM PERFORMANCE

The function of the containment system for an SI is to prevent or minimize escape of leachate, gases, solids, and bacteriological species from the impoundment into the environment. The containment system may frequently consist of a liner (for the bottom and sides), a cover (for the top), and any leachate or gas collection equipment. This section examines liner performance; covers are discussed in Section 3.4. The general intent of this section is to provide an overview of factors that influence liner performance and considerations for evaluating liner deterioration. A more detailed discussion of liners for waste impoundments describing liner types, design criteria, performance, and construction can be found in the document "Lining of Waste Impoundment and Disposal Facilities."[23]

3.2.1 Factors Affecting Performance/Life

Numerous factors and historical events that can occur during the useful life of an impoundment and effect liner performance should be considered in developing and assessing closure plans. Liner damage can be caused by interactions with the impounded waste, physical factors such as earth movements or meteorological conditions, and improper installation, use, or maintenance procedures.

Waste Composition

The single most critical factor affecting the performance of a liner is the chemical composition of wastes. Liner materials should always be tested for chemical resistance to wastes (e.g., ASTM Method D471). Such testing should be part of the liner selection process and should precede addition of any wastes with a composition different from that for which the liner was designed. Examples of waste/liner compatibility test programs are described in references 24 through 27. Observed impacts include chemical and biological attack leading to a breech in the liner, dissolution of the liner, and an increase in permeability of the liner.

The chemical compatibility of several liner materials with seven different industrial wastes is shown in Table 3-1. Since liner material composition, waste composition and concentration, and environmental conditions vary considerably, the compatibility ratings provide only general guidelines.

Table 3-1. Liner and Industrial Waste Compatibilities[28]

Liner material	Industrial waste[a]						
	Caustic petroleum sludge	Oily refinery sludge	Acidic steel pickling waste	Electroplating sludge	Toxic pesticide formulations	Toxic pharmaceutical waste	Rubber and plastic
Flexible synthetic membranes							
Polyvinylchloride (oil resistant)	G	G	F	F	G	G	G
Polyethylene	G	F	F	F	G	G	G
Polypropylene	G	G	G	G	G	G	G
Butyl rubber	G	P	G	G	F	F	G
Chlorinated polyethylene	G	P	F	F	F	F	G
Ethylene propylene rubber	G	P	G	G	F	F	G
Hypalon	G	P	G	G	F	F	G
Soil sealants							
Soil cement	F	G	P	P	G	G	G
Admixed materials							
Soil asphalt	F	P	P	P	F	F	G
Asphalt concrete	F	P	F	F	F	F	G
Asphalt membranes	F	P	F	F	F	F	G
Natural soils							
Soil bentonite (saline seal)	P	G	P	P	G	G	G
Compacted clays	P	G	P	P	G	G	G

[a] P = Poor, F = Fair, G = Good

Briefly, rationales for the ratings are:

- Caustic petroleum sludge is alkaline and contains salt components; therefore soil sealants, admixed materials, and natural soils would be subject to attack. This waste may contain certain hydrocarbons that could attack the asphalts and synthetics, with the possible exception of polyethylene and polypropylene.

- Oily refinery sludge contains hydrocarbons, phenols, and heavy metals, but has low salt and alkaline concentrations. Asphaltic and synthetic liners (with the exception of oil resistant types) will not perform well.

- Acidic steel pickling wastes (high acid and salt concentration) will attack soil-based liners. If the waste is introduced to the pond at an elevated temperature, asphaltic and synthetic liners may not be suitable; however, rubber and some polyethylenes can be used.

- Electroplating sludges contain heavy metals and salts that attack soil-based liners. Asphalt and thermoplastic membranes are rated "fair" since these wastes may also contain organic additives.

- Toxic pesticides and pharmaceutical wastes are assumed to contain as much as 25 percent organics; therefore, only natural soils, soil cement, and the oil resistant membranes are considered suitable

- The primary pollutants in rubber and plastic wastes are oil, grease, acids, bases, and suspended solids in concentrations sufficiently low so that all liner materials could be suitable

It must be emphasized that the evaluation of liner performance or assessment of an in-place liner should be based on directly related tests and not general guidelines as given here.

Physical Factors

Physical factors such as earth movement, temperature variations, rainfall, and sunlight can significantly degrade liner performance. Earth movement can fracture the more rigid materials such as natural soils and concretes. In some cases they may be self-sealing (i.e., bentonite can expand to fill cracks); however, other physical and chemical factors can negate any self-sealing capability.

Freeze/thaw cycles and freezing itself can seriously degrade liner performance. Temperature-induced stress can cause fractures. Some of the plastic materials become brittle at low temperatures and suffer property degradation at high temperatures.

Some of the flexible polymeric membranes can be degraded to some extent by exposure to sunlight (ultraviolet light) and ozone. These materials are classed as exposable and unexposable. Those that are resistant to sunlight and ozone, such as the synthetic rubbers, are termed exposable. A service life for most exposable liners of 20 to 25 years under normal atmospheric conditions can be expected. Under similar conditions, unexposable materials can be expected to perform 10 to 15 years.[29] In both cases, however, it is recommended that the liner be covered with earth.

Site Preparation/Installation

The performance and lifetime of the most carefully selected liners can be severely degraded by improper construction/installation procedures. There are three distinct phases of construction -- subgrade preparation, liner installation, and liner protection. General considerations are discussed in the following paragraphs, while specific details are outlined in reference 23.

Any liner should be built on a firm base to prevent differential settlement of the subgrade that can result in loss of liner integrity. The soil should be well compacted and devoid of surface irregularities; construction during wet or cold weather should be avoided. Foreign objects such as rocks, roots, and stumps should be removed as should any nearby vegetation that might root into the liner. A soil sterilant may be necessary to inhibit plant growth.

Most liner materials require specific and unique installation procedures. Soil bentonite may require prehydration and should be kept moist to maintain stability. Hot sprayed asphalts must be applied in several thin coats to prevent bubbles; drying times and application rates vary. Polymeric materials must be carefully seamed and anchored.

In many cases, liners also require some sort of protection -- usually provided by a layer of soil.[23] Heavy equipment, particularly that with crawler treads, should not be allowed directly on the liner. As previously discussed, some polymeric liners must be protected from ozone and ultraviolet attack.

3.2.2 Assessment of Liner Condition and Effectiveness

There are basically two approaches to evaluating the condition of a liner. The first is an indirect approach and involves a review of the original design considerations, construction technique, wastes stored, and historical operational records. The second and direct approach is to test the impoundment for leaks or deterioration of the liner. Both should be part of closure plan development and evaluation.

The indirect approach includes activities such as:

- Reviewing operating records to determine the type and composition of wastes
- Generalized waste/liner compatibility analysis
- Examining liner material/waste composition test results
- Examining construction and maintenance records

- Reviewing any site problems that may indicate a leak
- Visually observing surrounding vegetation
- Comparing estimated lifetime of the liner with the containment requirements of the wastes
- Assessing the degree of risk from breech of the liner

Consideration of these factors may be sufficient to conclude that it is not reasonable or practical to close the impoundment without removing the hazardous wastes. However, if closure as a landfill with the waste remaining in place is a possibility, the direct assessment should be conducted.

There are several techniques for direct liner effectiveness testing. Some or all of these techniques may be appropriate for individual site specific closure considerations. These methods include using a leachate detection system, extracting and examining a portion of the liner, and monitoring the ground water in the vicinity of the impoundment.

Leachate Detection System

There are two basic types of SI leachate detection systems that can be installed when the liner is constructed. The first consists of a series of perforated pipes placed beneath the liner. Any leachate that may penetrate the liner is collected in these pipes and can be withdrawn and tested. However, the location of the leak cannot be determined with this method.

The second system consists of a series of metal pins driven into the ground under the liner and interconnected so that electrical current can be applied. The pins are used to take resistivity readings of the soil between any two pins. To define a leachate plume, the method relies upon the fact that the conductivity of the ground water is inversely proportional to the resistivity measured in a section of earth containing that ground water. Since the conductivity of a leachate is generally much higher than that of fresh ground water, a sharp decrease in apparent resistivity will occur if leachate is present in the measured section. However, resistivity is subject to error in interpretation with many natural and manmade field conditions. In addition, this method has been shown to have a limited life, which may be significantly less than that of the impoundment.

Liner Examination

In some cases it may be desirable to directly examine the liner material for chemical or biological attack by extracting a sample of the liner. This may be particularly true of asphaltic and polymeric liners. A technical and economic review of three techniques for this (the use of a dragline, backhoe, and caisson) is given in reference 30. Tests of the liner may be used to evaluate its deterioration and expected lifetime.

Ground Water Monitoring

Leachate migration into ground water has a three-dimensional plume, the exact location and extent of which is very difficult to predict. Therefore, it is usually necessary to use wells at various locations within the aquifier to extract samples. Contamination is detected by changes in ground water composition that can be related to the wastes or by the presence of major waste constituents in the ground water at levels in excess of background concentrations. If the wells were not in place prior to construction of the impoundment, samples of ground water "upstream" (hydraulically up-gradient) of the impoundment may be used as reference samples.

3.3 POTENTIAL FOR WASTE MIGRATION

The potential for waste migration from an SI exists whenever residual contaminants are in a liquid or water soluble form. Several processes control the rate and extent of waste migration. They include:

- The solubility and rate of solution of the contaminant
- The balance between carrier fluid inputs and outputs from the SI
- The ability of the soil to restrict the movement of contaminants by soil-solution interactions

The first process is the subject of Section 3.1 and is not discussed further. The second and third processes are discussed in this section.

3.3.1 Water Balance

An estimate of leachate quantity generation at an SI facility is a critical factor in the environmental assessment of the site. The water balance is a quantitative statement of the relationship between the total water gains and losses of an impoundment over a given period of time and is, consequently, a tool for estimating leachate quantities and generation rates.

Several reports are available that document the use and application of water balance theory to landfill sites.[31,32,33] The manual "Hydrologic Simulation on Solid Waste Disposal Sites" [49] Provides computerized technique for simulating the hydrologic characteristics of waste sites, therefore, the following discussion is limited to a brief summary of general points to consider.

Mathematically, the water balance may be expressed in terms of flow continuity, for a given time interval, or

$$\text{Onsite accumulation} = \sum \text{inputs} - \sum \text{outputs}$$

If steady-state conditions are assumed to apply, the onsite accumulation term becomes zero. Therefore,

$$\sum \text{inputs} = \sum \text{outputs}$$

Seven principal input and output components of a hypothetical closed surface impoundment include: (1) precipitation, (2) surface runoff onto the impoundment, (3) surface runoff from the impoundment area, (4) evapotranspiration, (5) ground water underflow in, (6) ground water underflow out, and (7) infiltration or seepage. The illustration in Figure 3-1 is general and assumes that the impoundment liner is leaking or nonexistent. It is further assumed that surface runoff can enter the site from uncontaminated areas. In practice, such runoff should be diverted away from the site, eliminating this component. The illustration deals with a closed SI; therefore, liquid waste has not been included as an input component.

As illustrated in Figure 3-1, inputs are limited to precipitation falling directly on the site (including irrigation water if necessary) and surface runoff onto the site. Outputs occur as evapotranspiration, surface runoff from the site, and infiltration. Since the system has been defined to be in a steady-state condition, infiltration of surface water may be assumed to move down through the waste material and directly join the ground water underflow or form a leachate plume. The factors that affect the magnitude of each term are discussed in the following paragraphs.

Inputs

Except in cases where the SI is placed directly within a water table, precipitation represents the principal source of water into an SI. The frequency, amount, intensity, duration, and form of precipitation represent important considerations for water balance calculations as they influence both rainfall volume and runoff estimates. Precipitation varies considerably year to year. Therefore, the use of mean precipitation data can be considered a gross approximation at best. "Design" precipitation estimates can be generated through statistical analysis of past precipitation events. Precipitation data derived in such a fashion provide information on the percentage of time that rainfall is equal to or greater than a given value. Thus, water balances can be calculated for a given degree of risk. Historical precipitation data are generally available from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, Asheville, North Carolina. Precipitation intensity, duration, and physical form (i.e., rain, sleet, and snow) are factors that affect runoff volume and are discussed in a subsequent section.

Surface runoff represents a significant water input only where improper design allows runoff to enter from upslope. This possibility exists for SI facilities that have been constructed in hillsides or where they do not have surrounding dikes.

Outputs

Evaporation reduces the total amount of water available for runoff and infiltration and can occur from a free water surface, fallow soil, and snow. Additionally, evaporative processes can transport soluble contaminants through thin (approximately 1 foot) surface cover material, resulting in surface contaminants amenable to resolution, runoff transport, and dust reentrainment to the air. Surface containment accumulation can also damage vegetative cover.

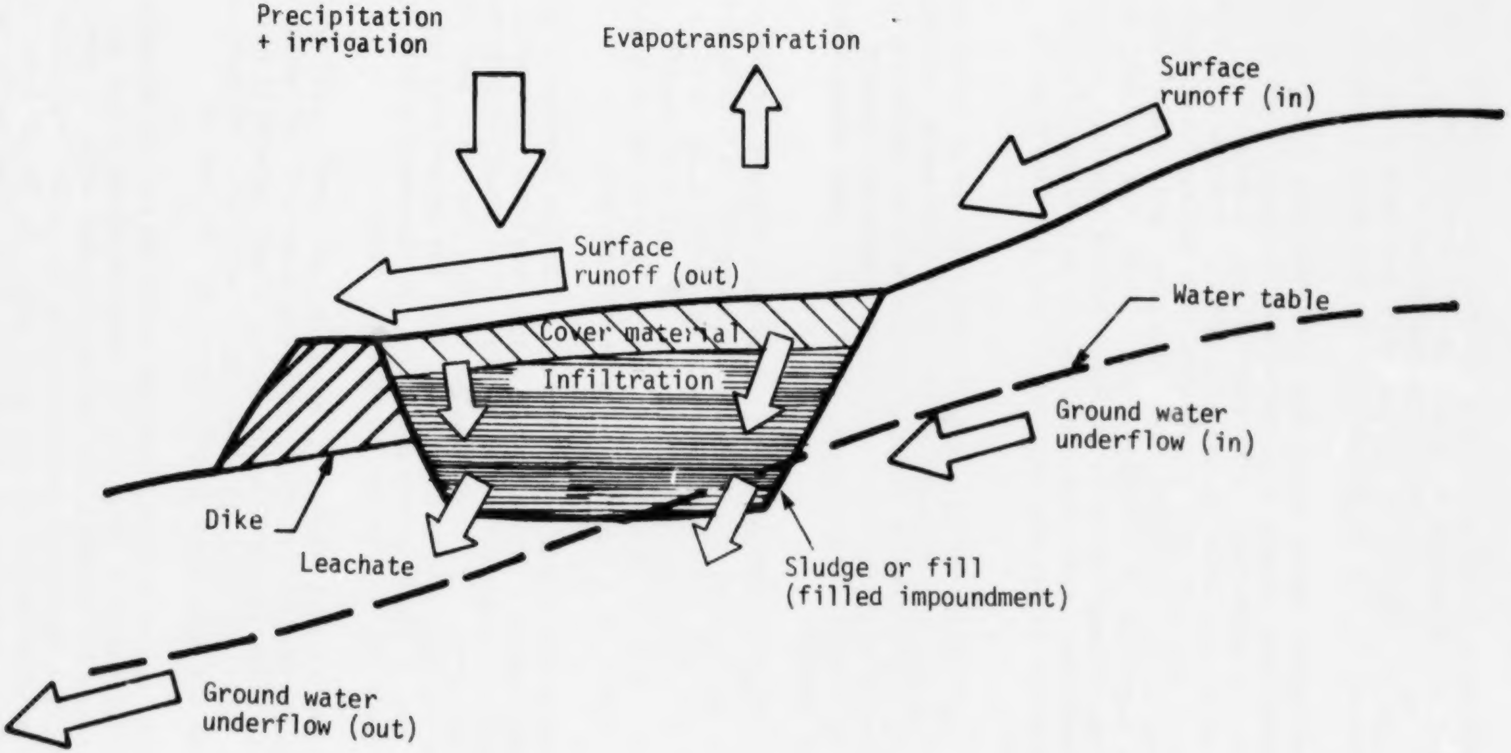
Precipitation
+ irrigation
Evapotranspiration
Surface
runoff (in)
Surface
runoff (out)
Water table
Cover material
Infiltration
Ground water
underflow (in)
Dike
Leachate
Sludge or fill
(filled impoundment)
Ground water
underflow (out)

Figure 3-1. Simplified Water Balance for Filled Surface Impoundment

The rate of evaporation is directly proportional to atmospheric vapor pressure that, in turn, is dependent on water and air temperature, wind speed, atmospheric pressure, salinity, and the nature and shape of the evaporative surface. Regional data on evaporation is generally available from the Environmental Data Service or can be estimated from the above parameters.[4]

Transpiration processes remove water from soil moisture and from shallow ground water via vegetational growth and, therefore, is significant only when the surface soil cover is vegetated. Like evaporation, transpiration reduces the total volume of water available to the site and can transport contaminants upward, particularly if the root zone penetrates into the residual waste. Temperature, solar radiation, windspeed, soil moisture, and type of vegetative cover all affect the magnitude of transpiration. Often, the distinction between evaporation and transpiration is unclear and the combined moisture loss via these two processes (evapotranspiration) is estimated. Methods of estimating evapotranspiration are straightforward and are discussed in references 33 and 34.

Runoff from SI facilities can be a significant fraction of total offsite migration volume. However, the interaction of runoff with waste contaminants (and therefore offsite transport) is limited to the mass of contaminants brought to the surface by capillary or evaporative processes. Runoff transport of waste contaminants can also be significant when impoundments are improperly covered or sealed.

The amount of surface runoff is dependent on many factors including intensity, duration, and form of precipitation; antecedent soil moisture conditions, permeability and infiltration capacity of the cover soil, slope, and amount and type of vegetative cover. The use of "rational runoff coefficients," as described in reference 34, generally provides a reasonable estimate of surface runoff as a function of these parameters.

Infiltration represents the primary mechanism for the downward migration of waste-derived constituents. Four processes are involved: (1) entry through the cover soil (or residual waste strata, if no cover is present), (2) storage within the soil, (3) transmission through the soil, and (4) deep drainage through the residual waste strata and into the underlying soil. A factor limiting any one of these processes (i.e., an impermeable soil cover) can significantly reduce the net volume of vertical flow.

Rainfall characteristics (intensity, duration, and form), soil properties (texture, structure, permeability), and vegetative cover all influence the rate of infiltration. Fine textured soils (i.e., clays) generally have the lowest infiltration rates and make excellent cover material. Methods used to quantify infiltration are described in references 31, 35, and 36.

Once water enters the soil below residual waste strata, it advances as a moisture front as illustrated in Figure 3-2. Water reaching a dry soil moves slowly because the hydraulic conductivity of unsaturated soils is generally low. The effective cross sectional area available for water transmission is small in dry soils; adsorption and retention of water by the soil matrix is also involved. However, water behind the wetting front flows quite rapidly

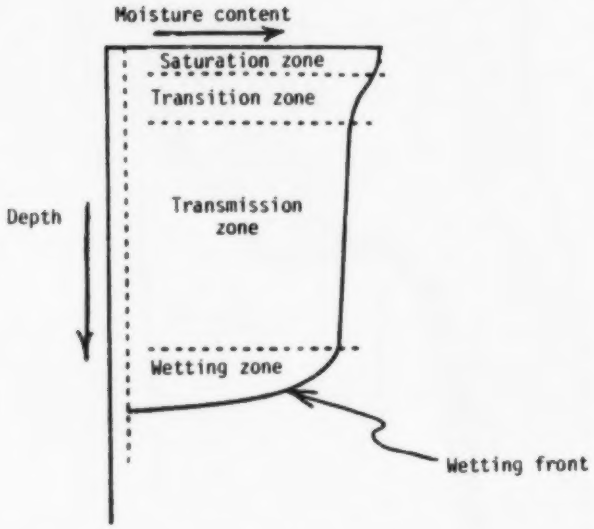

Figure 3-2. Moisture Distribution During Infiltration Through an Unsaturated Soil[5]

because the hydraulic conductivity is higher. Thus, water "piles up" at some distance behind the wetting front until the soil is nearly saturated and then moves onward. These processes take place in all soils; however, in very fine grained soils, moisture migration is so slow as to be negligible. This process of slow infiltration continues until the wetting front reaches a zone of saturation or the ground water table.

Ground Water Underflow

Detailed field investigations are required to evaluate the volume of ground water underflow. A complete ground water flow evaluation would provide information on seasonal depths to ground water; rate and direction of ground water flow; the location of ground water recharge and discharge areas; the types of aquifers below the site; the rate of site infiltration relative to total ground water underflow, the presence and location of fissures in underlying bedrock, and specific gravity of the leachate and ground water mass.[31] Techniques described in reference 31 can be used to arrive at reasonable approximations of both ground water inflow and outflow.

3.3.2 Attenuation Mechanisms

The simultaneous flow of water and solutes is a phenomena that is associated with the leaching of hazardous wastes. The movement of solutes through (and above) the soil profile depends on the combined action of bulk transport, diffusion-dispersion, and soil-solute interactions. The number of variations that can occur in aquifer pollution situations are virtually limitless.[38] Figures 3-3 and 3-4 represent two examples of hypothetical

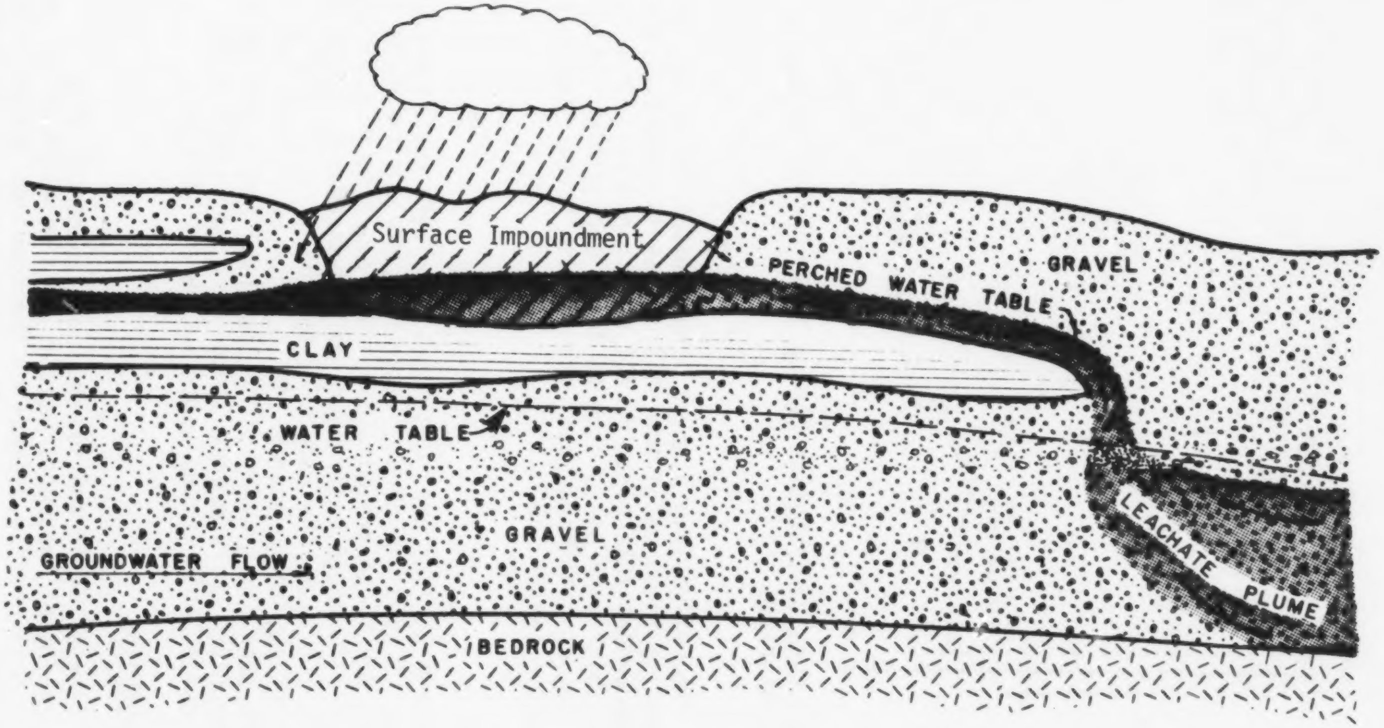
Surface Impoundment
PERCHED WATER TABLE
GRAVEL
CLAY
WATER TABLE
GRAVEL
GROUNDWATER FLOW
LEACHATE PLUME
BEDROCK

Figure 3-3. Abandoned Gravel Pit with a Clay Layer at Its Base[31]

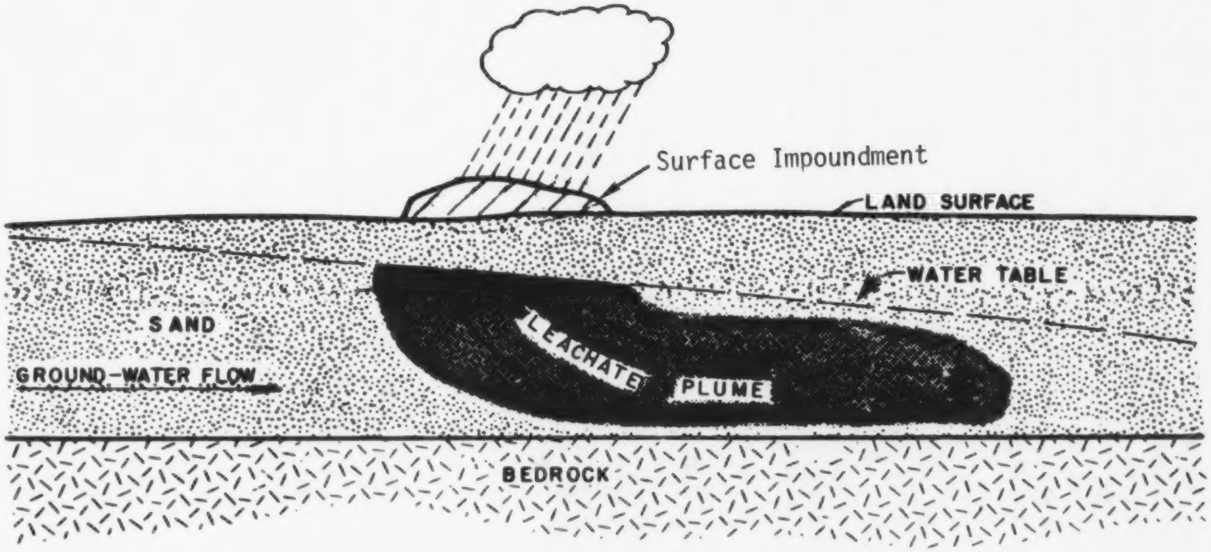
Surface Impoundment
LAND SURFACE
WATER TABLE
SAND
GROUND-WATER FLOW
LEACHATE
PLUME
BEDROCK

Figure 3-4. Single Aquifer with a Deep Water Table[31]

hydrogeologic pathways for aquifer contamination. Additional pathways are presented in references 31 and 38.

Bulk transport or mass flow represents that quantity of solute that is transported at a rate and direction identical to that of the transporting medium (usually water). Diffusion/dispersion describes the lateral flow of solutes during transport. Diffusion is caused by random thermal motion of the solute molecules, while dispersion describes mixing caused by the tortuous flow of water around individual grains and through pores of various sizes. Soil-solution interactions occur when the solute reacts with the soil, further modifying the distribution of the solute between the solution and soil phase.[31,39]

Mathematically, the movement of solute has been described in reference 40. Simply stated, the rate of change of solute concentration C is a function of diffusion/dispersion, bulk transport, and soil solution interactions. Three cases are presented describing how each process effects the movement of solutes. For each case, "C_0" represents the initial solute concentration entering the soil column and "C" represents the concentration of solute leaving the column.

Solute Transport by Bulk Transport Only

Figure 3-5 shows a breakthrough curve for 100-percent bulk transport through a soil profile of finite length. A sharp rise in the ratio C/Co is noted because there is no opportunity for mixing. Solutes move at a rate equivalent to that of the transporting fluid. This type of transport almost never occurs in soils or streams.

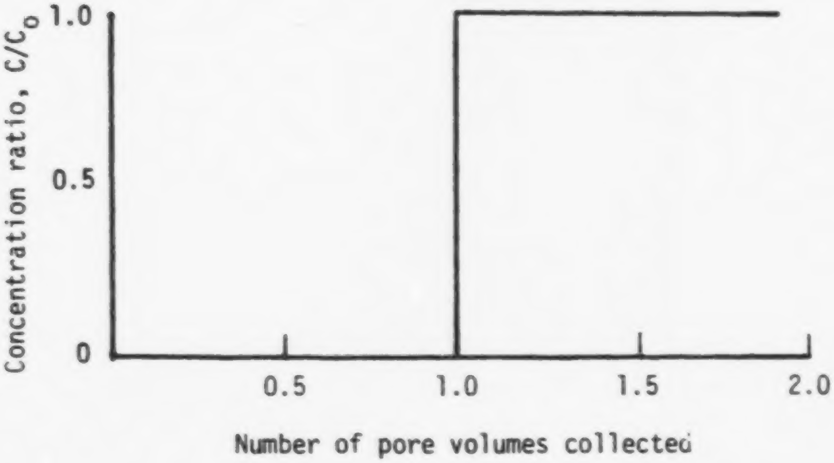

Figure 3-5. Breakthrough Curve for Bulk Transport of Solutes[39]

Solute Transport by Diffusion-Dispersion and Bulk Transport

Figure 3-6 illustrates a series of breakthrough curves for bulk transport combined with diffusion/dispersion. An instantaneous jump in C/Co is no longer observed. Instead, C/Co rises gradually as effluent volume (or time) increases. The combined effects of diffusion, viscous drag, and dispersion result in a more complex flow pattern that changes as a function of pore size distribution (curves A, B, C). This type of behavior is characteristic of noninteracting solutes (chlorides, sulfates, nitrates, etc.).[39]

Solute Transport by Bulk Transport and Diffusion/Dispersion with Soil-Solution Interaction

Figure 3-7 illustrates the effect of soil-solution interaction on solute transport. In this case, the breakthrough curve shifts to the right reflecting the longer time required for solute transport when soil-solution interactions are present.[41]

The type of interactions that commonly occur in soil are presented in Table 3-2. All listed mechanisms vary in magnitude as a function of waste and soil characteristics. Soil pH, cation exchange capacity, organic matter content, texture, and permeability are generally considered "master variables" because they influence the rate and direction of interaction.

Several mechanisms are often associated with the removal of individual waste components as illustrated in Figure 3-8. Detailed discussions of these interactions are beyond the scope of this report, but can be found in references 36, and 42 through 46.

3.4 COVER SYSTEMS

An integral step in the closure of an SI is the design and fabrication of a cover. This is needed when the wastes are left in the impoundment after closure and a closure plan similar to that required for a landfill is implemented. In the case where wastes are removed from the impoundment, a cover designed for purposes of waste isolation is not necessary. However, some degree of site reclamation may be necessary for the control of erosion, drainage, and wind blown dust as well as for safety, aesthetic, and end-use considerations.

For an SI closed as a landfill, the cover must function primarily to:

- Control the migration of pollutants
- Control surface water infiltration
- Prevent erosion
- Control potentially harmful gas movement
- Support construction vehicles

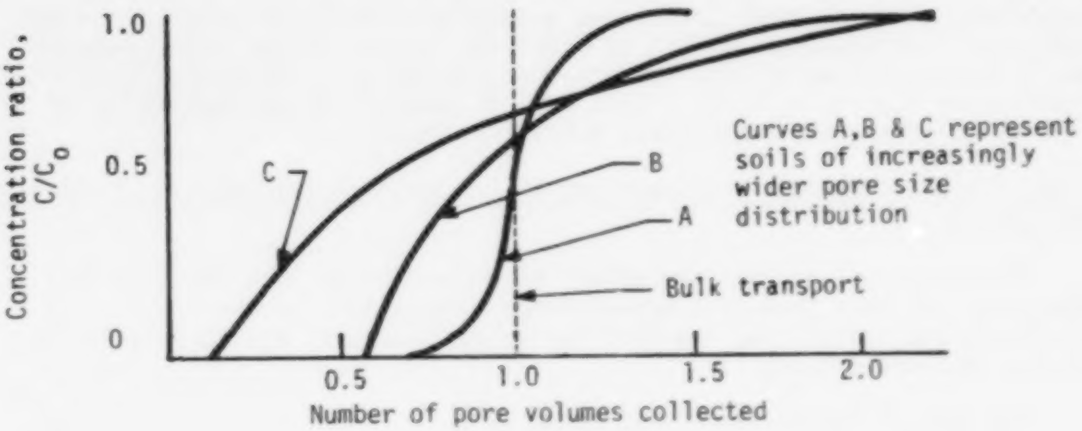

Figure 3-6. Breakthrough Curve for Bulk Transport and Diffusion/Dispersion[39]

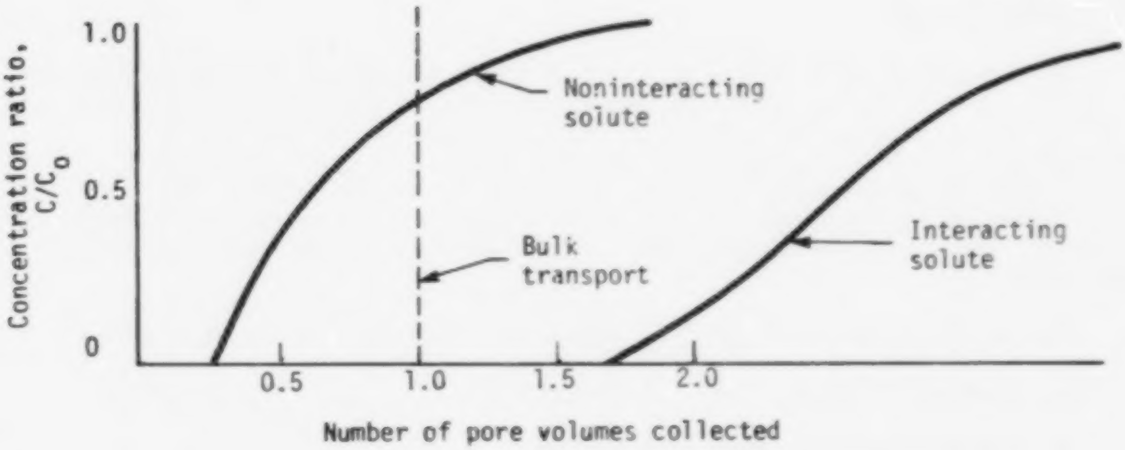

Figure 3-7. Breakthrough Curve with Soil-Solution Interaction[41]

Table 3-2. Types of Soil-Solute Interactions[36,42-46]

Biological	Chemical	Physical
Transformation	Cation exchange	Filtration
Degradation	Anion exchange	Dilution
Volatilization	Cation-dipole interaction	Decay
Crop Uptake	Hydrogen bonding	
	Van der Waals attraction	
	Hydrophobic bonding	
	Specific ion sorption	
	Precipitation	
	Chelation	

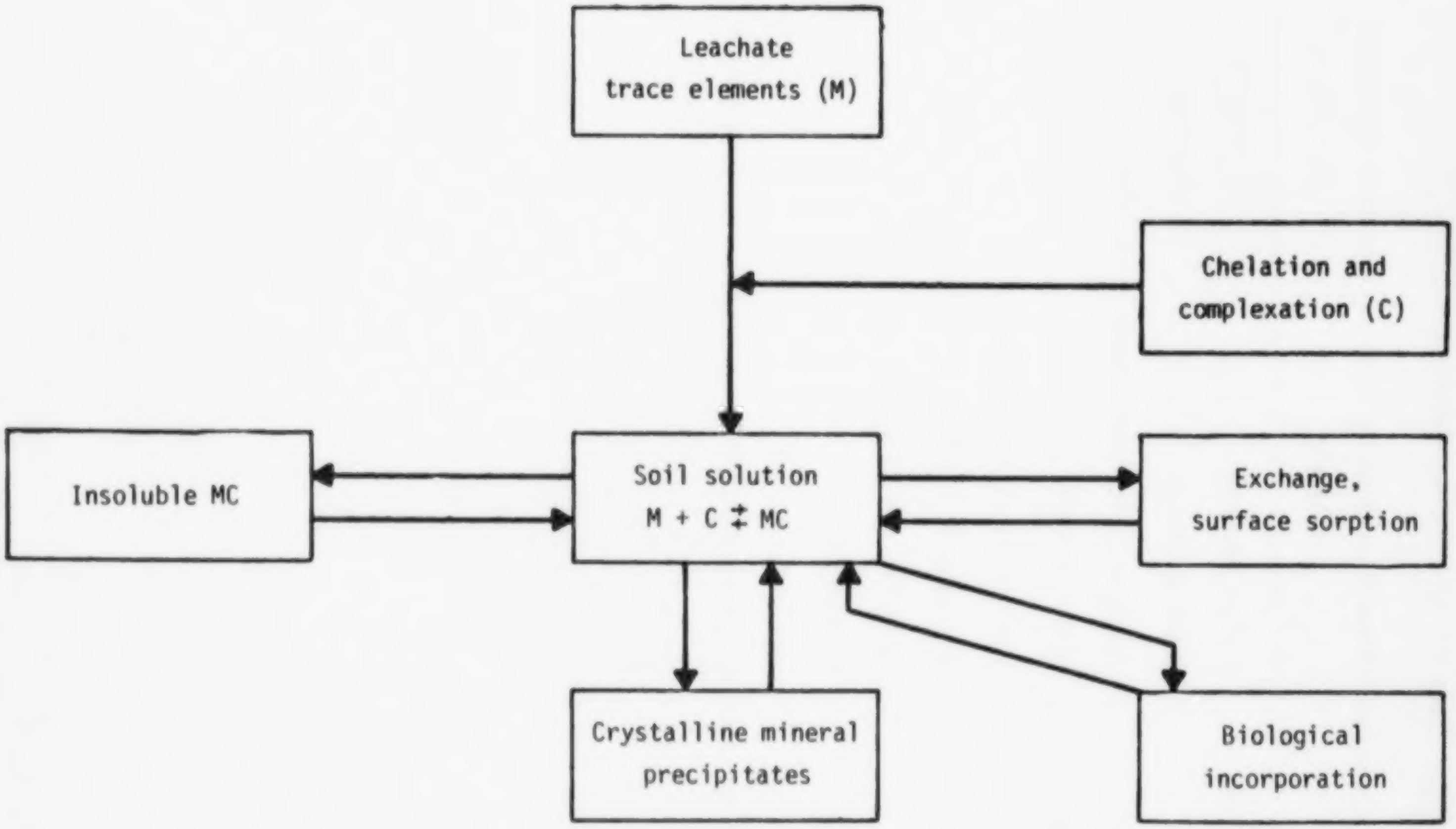
Leachate
trace elements (M)
Chelation and
complexation (C)
Insoluble MC
Soil solution
M + C ⇄ MC
Exchange,
surface sorption
Crystalline mineral
precipitates
Biological
incorporation

Figure 3-8. Trace Element Controls in Soils[45]

In addition, the cover will function to meet aesthetic considerations by controlling any noxious odors and providing a base for the establishment of vegetation. The functions of a cover for a closed SI are usually complexly interrelated. For example, a cover designed to impede infiltration and percolation of surface water may call for a clay layer while dust control and wind erosion considerations would best be met by a layer of coarse-grain-sized sand. Where apparent conflicting functions exist, priorities must be established on a site-specific basis.

In designing and specifying a cover to meet the established functional objectives, reference 47 should be consulted. This design and construction manual makes general recommendations with regard to covers, presents details of each cover function, reviews pertinent characteristics of soils and other materials, and proposes specific design methods taken from the present waste disposal state of the art.

Upon development of a proposed design, reference 48 presents a procedure for evaluating cover designs for closure impoundments. This manual outlines guidelines to be used to evaluate the pertinent elements of the design. These elements include: soil test data, site topography, climatological data, cover composition, thickness, placement, cover configuration, site drainage, vegetation, post-closure maintenance, and contingency plans. Persons involved in assessing the adequacy of surface impoundment closure plans should refer to this manual. One step in evaluating cover design involves an assessment of cover thickness with respect to infiltration, surface runoff, and evapotranspiration. The evaluator is referred to reference 40 where the details of a recommended computerized water balance procedure are outlined.

3.5 POTENTIAL FOR CONSOLIDATION OF WASTES

Almost all SI's are intended for retention of aqueous wastes on either a full- or part-time basis. These aqueous wastes contain solids (sludges and slimes) or will produce solids by precipitation as a result of solar evaporation and/or chemical reaction upon mixing of different aqueous wastes. Consequently, dewatering of the SI prior to closure will result in a layer of residual waste solids left on the bottom of the impoundment. These solids will be saturated with water. If the impoundment has a soil bottom or a clay liner or both, these soils will be saturated with water as well. If these saturated or even partially saturated solids and soils are backfilled with an earth or clay cover, the potential exists for significant consolidation of the residual waste solids and, to a lesser degree, the clay liner and/or soil beneath the waste solid sediment.

3.5.1 Stages of Consolidation

Consolidation is defined as the process of reducing the volume occupied by a soil mass. This volume reduction occurs either at the expense of the void volumes between the solid particles or by reduction of the volume of the solid particles themselves. Consolidation occurs in stages: primary, secondary, and tertiary.

The initial step of the consolidation process (primary) is due to a decrease in the water content of fully saturated waste. The rate of primary consolidation is controlled by the rate at which water can be removed from the waste either by overburden pressure forces or capillary forces. This rate is of course controlled by the permeability or hydraulic conductivity of the waste strata and the surrounding soils. The second step of the consolidation process (secondary) results from compression of the constituent solid waste itself. The third step of the consolidation process (tertiary) results from reduction of the actual mass of the waste solid particles. This may occur as a result of leaching (dissolution of waste solids in water); gasification by chemical reaction; and biological oxidation, either aerobic or anaerobic. Tertiary consolidation can occur in parallel with either primary or secondary consolidation.

3.5.2 Impacts of Waste Consolidation

The primary impact of waste consolidation is a reduction in the surface elevation of the covered site. When this reduction occurs to different degrees at different points on the site it is called differential settlement. If a covered impoundment site is to be used for either aesthetic or public purposes, the surface subsidence from consolidation must be prevented. Severe cases of subsidence result in very uneven ground contours and could even lead to cracking of the surface and or fracture of the cover. Any type of construction on the site would be endangered by subsidence, particularly differential settling.

Serious subsidence problems can result in creation of one or more surface depressions that will act as runoff catchment basins. This will result in standing water on the cover, a condition that will significantly increase the rate at which water can infiltrate a porous or semipermeable cover. Increased infiltration will result in increased leaching that, in turn, can result in tertiary consolidation due to dissolution of residual waste solids. The amount of consolidation depends on the quantity of leachable constituents. The weight of the water impounded by surface depressions can also lead to additional secondary consolidation of the residual waste solids. The overall result would be additional subsidence and increased discharge of leachate. It must be remembered that consolidation of an SI is a dynamic process and that deformation of the cover surface will occur with time. Consequently, regrading of the cover surface may be necessary to minimize the effects of localized subsidence.

Perhaps the most serious consequence of differential consolidation is that the cover may fracture. This could result in the production of a direct channel to the residual waste solids that could allow direct access of surface water to the residual wastes. The fracture would also act as a discharge channel for gases and/or contaminated leachates.

3.5.3 Mechanism of Consolidation

The extent of consolidation primarily depends on the thickness of the residual waste sediment layer. Differential settling will be a potential problem when the thickness of the residual waste sediment varies within the site. The physical characteristics (grain size, pore volume, etc.) and the chemical characteristics (solubility, gasification potential, organic content, etc.) also affect the extent of consolidation.

Primary Consolidation

By definition, primary consolidation results from the drainage of "connate water" from the voids between the waste solid particles. Thus, the extent of primary consolidation will depend on the amount of connate water left in the waste sediment layer at the time of backfill and cover. The rate of primary consolidation will be controlled by the rate at which water can drain from the sediment layer. The drainage can occur by several mechanisms:

- The primary mechanism is drainage through the liner and surrounding soils. In the case of unlined impoundments, this drainage is controlled by the permeability of the surrounding soils. In the case of faulty liners, the size of the fault together with the permeability of the waste sediment and the permeability of the soils in the vicinity of the faults controls.
- A secondary mechanism is assimilation of moisture by the backfill/cover material. If these materials are relatively dry at the time of placement, capillary tension can move connate water upward into this material. The extent to which this occurs will be controlled by the particle size of the backfill/cover and the degree of compaction achieved. In impoundments with an intact liner of low permeability, this may be the primary mechanism for connate water removal from the sediment layer.
- In some cases, when the liner is intact and connate water drainage is expected to proceed slowly or not at all, it may be desirable to "engineer" one or more drainage paths through the liner to a liquid collection system.

Secondary Consolidation

By definition, secondary consolidation is due to plastic creep or deformation of the residual sediment under the force of overburden stress. Also, some solids undergo a volume shrinkage as the water content decreases (clays are one example of the shrinkage phenomena). Clearly the extent of secondary consolidation and the rate at which it occurs are very specific to the physical characteristics of the sediment (rates of creep under specific levels of overburden pressure).

A situation of particular concern is the case of a covered impoundment hydraulically sealed to the extent that the residual waste solids cannot be completely drained of connate water. In this case, the residual waste solid will remain a flowable or plastic solid and, under the force of constant overburden pressure, will remain in place in a more or less metastable condition. If an unbalanced overburden stress is created (i.e., construction of a structure on part of the cover), the residual waste can flow to the area of lesser overburden stress. This results in settlement of the stressed overburden area (structure site) and rising of the unstressed overburden area. If significant, this latter action could fracture the cover and exude waste solids to the surface.

Tertiary Consolidation

Many mechanisms can contribute to reduction of the actual mass of sediment solids. The most common include:

- Leaching -- Requires the supply and drainage of fresh (or at least uncontaminated) water and soluble wastes and can be controlled by the site water balance
- Gasification -- Requires wastes capable of generating a gas by chemical reaction (carbonates, sludges, etc.). The reactions are generally pH controlled and are facilitated by water.
- Biochemical degradation -- Requires organic wastes, a supply of water, and either aerobic or anaerobic conditions. The reactions are severely inhibited by toxic wastes.

The potential for tertiary consolidation is highly specific to the waste, type of impoundment, method of closure, and site water balance.

3.5.4 Timeframe of Consolidation

Primary consolidation occurs relatively rapidly. Significant consolidation has been observed over time periods ranging from several weeks to several years in full-scale studies of soil. The timeframe is highly dependent on the ability of the site to drain water and, consequently, engineered drainage pathways can accelerate this otherwise slow process. Such drainage systems may consist of infiltration trenches containing perforated drainage or tiles backfilled with previous material such as sand. Another means for shortening the timeframe would be to surcharge the cover with surplus material to promote consolidation.

Secondary consolidation is relatively slow. In some cases, no effects can be seen at all for many years until the imposition of an uneven surface stress upsets the hydraulic equilibrium, and flow and/or deformation occur.

The rate of tertiary consolidation is highly specific to the operative mechanism. No effect may be seen at all until local conditions occur that activate one or more mechanisms. Leaching is clearly dependent on the water throughput. Biological rates are relatively slow and environmentally constrained. The presence of toxic materials may inhibit rates or prevent activity entirely for many years. Chemical consolidation rates are dependent on a supply of alkaline or acidic water and are constrained by the rates of supply.

3.6 POST-CLOSURE USE OF THE SURFACE IMPOUNDMENT SITE

Limitations of subsequent site uses should be considered prior to closure of an SI. This section describes those site and waste characteristics that will affect site uses and lists methods of controlling site use. The selection and design of a cover system for a closed SI should take into account the post-closure land use. A planning study should identify uses that will:

- Control the migration of pollutants from the facility via ground water, surface water, and air
- Control surface water infiltration including prevention of pooling
- Prevent erosion

In addition to the above regulatory requirements, land use plans should promote the following objectives:

- Permanently upgrade the SI so that the land can be used in the most advantageous manner
- Promote the permanent conversion of the impounded wastes to a stable nonhazardous state
- Eliminate or minimize potential off-site conflicts with existing or future development through the careful siting and maintenance of an open space separation and utilization of natural buffers
- Be compatible with and complementary to existing natural conditions and help meet the future needs of the community

The land use planning process should also be integrated with surrounding land use and community needs. This process should be organized to provide information that will aid in establishing the threat to human health and the environment. A logical approach to site planning may include the following steps:[50]

1. Perform site inventory. The existing land use must be identified, and the impact of curtailment of current land use (whether it be recreation, open space, etc.) must be determined. The inventory might include topography, vegetation, water bodies, public facilities, etc. Information can be obtained from aerial photos, site visits, and review of public records. In addition, the sources listed in Table 3-3 can be consulted.
2. Evaluation of needs. To assess future needs, an evaluation of local plans for population, utility, and highway projections should be attempted. Local planning offices should be contacted to determine current land use policies for the area of consideration.

Table 3-3. Sources of Existing Information[2]

General information	Specific information	Source
Base map	General	County road department City, county, or regional planning department U.S. Geological Survey (USGS) office or outlets for USGS map sales (such as engineering supply stores and sporting goods stores) U.S. Department of Agriculture (USDA), Agricultural Stabilization and Conservation Service (ASCS) Local office of USGS County Department of Agriculture, Soil Conservation Service (SCS) Surveyors and aerial photographers in the area
	Topography and slope	USGS topographic maps USDA, ARS, SCS aerial photos
	Land use	City, county, or regional planning agency
	Vegetation	County agriculture department Agriculture department at local university
Soils	General	USDA, SCS District Managers, Local Extension Service USGS reports Geology or agriculture department of local university
Bedrock	General	USGS reports State geological survey reports Professional geologists in the area Geology department of local university
Ground water	General	Water supply department USGS water supply papers State or regional water quality agencies USDA, SCS State or federal water resources agencies Local health department
Climatology	General	National Oceanic and Atmospheric Administration Nearby airports

3. Identify alternatives and select completed site use. Using the information obtained above, an evaluation should be conducted noting advantages and disadvantages of each potential use. If site characteristics and constraints are known, alternative ultimate land uses can be evaluated in terms of technical feasibility and costs. The optimum site use can then be selected.

4. Select, design, and implement completed site use. After selecting completed site use, a master plan should be prepared. It should designate the scheme for cover soil stockpiling, maintaining positive drainage by regrading, revegetation, sediment control, leachate control, ground or surface water monitoring, and maintaining acceptable environmental and aesthetic conditions.

3.6.1 Site Use Limitations for Impoundments Closed as Landfills

The first option for SI closure is to leave wastes in the impoundment, dewater the solids, and close the site as a landfill. Under this option, the owner must consider all problems of site maintenance and access that are characteristics of landfills. A summary of major technological considerations is presented in Table 3-4.

Closure plans for SI's differ most from those of landfills in the need of solids dewatering and dike considerations. Neither of these items should adversely affect post-closure use of the site if completed. Consolidation of sludges to enable structural support of overlying building may require longer periods of time than for landfills. Post-closure site uses may also be limited due to closure cover (poor trafficability of soil, erosion by wind or water), dikes and levees (side and mass instability), gas production (affects on vegetation, safety to users, control devices), and surface water control devices or other contour changes.

Detailed consideration for preclosure site surveys is given in Section 4.6 for dike and levee stability and Section 3.7 for gas generation. However, such a survey should collect information to evaluate other less obvious site conditions that affect its subsequent usage. These include the following:

- Trafficability characteristics -- strength of site surface under repeated traffic (these characteristics are often measured by the rating cone index,[47] soil moisture, and slope index[52])
- Construction support characteristics -- wastes used in impoundments exhibit both an enduring potential for serious pollution and resistance to compaction. (Predictions on settlement can be made that are adequately reliable for engineering construction design use. Although the colloidal nature of sludges may keep them water-saturated for years, the impoundment can be designed for more rapid in situ stabilization if dewatering and drainage are incorporated.)

Table 3-4. Compatibility of Hazardous Waste Impoundment Features and Various Site Uses

	SI site uses upon closure				
Design features	Buildings	Parks, playgrounds, ballparks, golf courses	Parking areas	Agriculture	Open spaces
Subsurface water control					
Extraction well	C	RDA	RDA	C	C
Well point system	C	RDA	RDA	C	C
Cut-off walls	C	C	C	C	C
Subsurface drainage	C	C	C	C	C
Surface water control					
Cover	NC	C	C	C, affects techniques	C
Grading	NC	C, except ballparks	C	C	C
Diversion of surface water	C	C	NC	C	C
Levees/floodwalls	NC	NC	NC	NC	C
Drainage/erosion control	RDA	RDA	RDA	C, affects techniques	C
Air factors					
Passive gas control	NC	C	C	C, affects techniques	C
Active gas control	NC	C	C	NC	C
Control of bird hazard to aircraft	C	C	C	C	C
Surface area factors					
Covers	C	C	C	C, affects techniques	C
Access	C	C	C	C	C
Land buffers	NC	C for parks and golf courses	C	NC	C

C = Compatible, NC = Not compatible, RDA = Requires design alteration

- Vegetation growth characteristics -- surface flooding, ground water table, soil character, erosion by wind or water, and gas generation each directly effect site vegetation

3.6.2 Site Use Limitations for Impoundments Closed with Hazardous Waste Components Removed

Closed SI's that have insignificant remaining hazardous content are essentially reclaimed areas in terms of contamination by hazardous wastes. However, site changes that occurred during impoundment formation (i.e., dikes or excavated depressions) or hazardous waste removal (channels, excavations, treatment devices) should be reconditioned. Local regulations frequently require that upon closure of industrial or commercial operations, equipment and buildings be removed and the land be returned to its former natural state. Under such regulations, the removal of dikes, waste flow controls, and nonhazardous waste residuals would be completed and ground cover replanted. If an alternative site use is planned, lesser refurbishing of the site may be allowed. A listing of considerations limiting site post-closure use are presented in Table 3-5.

Table 3-5. Compatibility of Various Site Uses and Impoundment Features After Hazardous Waste Removal

	SI site uses upon closure				
Design features	Buildings	Parks, playgrounds, ballparks, golf courses	Parking areas	Agriculture	Open spaces
Subsurface water controls					
Wells	CIR	CIR	CIR	CIR	CIR
Subsurface drainage	C	C	C	C	C
Surface water control					
Cover	RDC	C	C	C	C
Diversion of surface water	RDC	C	NC	C	C
Levees/floodwalls	CIR	CIR	CIR	CIR	CIR
Air factors	C	C	C	C	C
Surface area factors	RDC	C	C	C	C

C = Compatible, CIR = Compatible if removed/dismantled, RDC = Requires design consideration

3.6.3 Considerations for Limiting Access

Completion of impoundment site closure frequently requires access restrictions. This is necessary to protect the site and both the general public and maintenance personnel. During closure operations site access may be limited by posting, entry controls, fencing, or other physical barriers. Entry controls would typically include fencing with gates across the access roads. Each entry gate should be well posted as should any readily accessible periphery with incidental auto or foot traffic. Company personnel or law enforcement officers should patrol sites on some periodic planned schedule. Impoundments near population centers or frequently used company land may require a chain-link fence or other secure access barrier. Subsequent to closure, attention should be given to access control for gas, surface water, or other pollutant control devices necessary to minimize nuisance or environmental hazards. If cover grading, levees, dikes, buffer zones, or floodwalls appear potentially inviting to users of recreational vehicles, additional access control should be installed. Consideration should be given to site uses compatible with cover maintenance, especially since use affects vegetation established for cover protection and surface erosion control.

3.7 AIR EMISSIONS

The potential emission of organic gases and fugitive dust is a well recognized impoundment problem that may appear or continue during and after closure if preventive control measures are not taken. Generally, organic air contaminants have not been measured in routine site surveys. Indeed, air contaminants are often completely neglected in deference to water (leaching) or solid (erosion, mass wastage) constituent losses during site survey sampling and analysis. Air emission sampling and monitoring at hazardous waste facilities has been carried out, and the results are described in reference 53. Technical considerations of potential emissions of gases and dust are discussed in the following subsections.

3.7.1 Gases Emitted From Impounded Materials

Gases may be emitted from an impoundment due to the vaporization of liquids, chemical reactions, or biological activity of the impounded solids and liquids, or by venting of entrained gases. Emission of organic decomposition gases (methane, hydrogen sulfide) from proteinaceous and cellulosic wastes, radon gas from uranium mill tailings, and harmful gas contaminants (chloroform, benzene, and trichloroethene) from chemical process waste impoundments have been measured and reported.[54] The emission of harmful gases such as methane, methylmercaptan, dimethyl-disulfide, & hydrogen sulfide from liquid and sludge industrial waste (notably sugar beet, pulp, and chemical processing industries) have been the subject of public concern and regulatory activity for many years. Various organic compounds may slowly but continuously volatilize under improperly closed impoundment conditions. Low boiling point organic materials including contaminated solvents, if improperly impounded, will emit vapor that can be hazardous because of its toxicity or ignitibility. Inorganic gases can also be emitted from impoundment surfaces. Oxidant gases (Cl_2 and O_3) may react with polymeric liner materials and organic materials. These gases either originate as entrained gases or as chemical reaction products. During closure of an active impoundment site, consideration must be given to the possible release of impounded gases as a result of closure operations or from biological or chemical activity.

Gases Entrained or Generated in Surface Impoundments

The traditional ponds, pits, lagoons, reservoirs, and other SIs used for hazardous liquid and solid waste disposal, industrial waste storage, sludge, or wastewater treatment prior to closure have exposed top surfaces. Both liquid and sludge surfaces will vaporize solvent and related hazardous organic compounds. Vaporized contaminants of greatest concern are the halogenated organics and aromatic hydrocarbons because of their toxicity. Solvents and inorganic fumes are also of major concern. The volatility of hydrocarbons are reported in a series of Hydrocarbon Processing Journals,[55] while information on pesticides is available from Spencer and Cliath.[56] The rate of waste volatilization in soil or impoundments is dependent on physical and chemical properties of the waste and the surrounding environment. Emissions into still air are slower than evaporation into the wind. Characteristic maximum vapor pressures increase with temperature. Vaporization of organics from water surfaces is affected by Henry's law constant but wind speed, temperature, and liquid turbulence also affect the rate.

Gases may be generated from chemical reaction of the impoundment contents or by biological activity on the carbonaceous components. Upon closure of a site, if existing organic and reactive constituents are not removed, gas generation may continue or even increase.

The organic matter in impounded sludges, whether lying in a discrete contained sludge layer or deposited within the subsoil in some distributed concentration, will undergo decomposition. Such biological degradation will change from aerobic to anaerobic, increasing especially after surface closure. Organic constitutents are gradually oxidized to intermediate products (organic acids and alcohols) and subsequently converted to gases and organic residues. Unfortunately, many reduced sulfur and volatile intermediate products may be vented before further stabilization.

The quantity of gaseous air emissions from impounded liquids or sludges varies widely. Laboratory studies of gas production in covered wet solid waste ranged from 22 to 45 ml/kg/day. The total amount varied between 2,600 to 183,000 ml/kg of waste.[57] In closed systems, this gas can build up pressure, break through cracks in the cover, and carry hazardous vapors, if present, along with it to the surface. Some gas generation rates for several industrial wastes impounded as liquids or covered are given in Table 3-6.

Impoundments containing hazardous components characterized by low boiling points (<100^{o}F and vapor density = 1.1) or low flashpoints must be assessed for potential gas generation. Both potential direct venting and possible reactions resulting in gas generation must be considered. Direct venting of solvents in large quantities is prohibited, but small quantities mixed with waste sludge are often held in outside open impoundments.

Table 3-6. Impounded Waste Gas Generation Rates[57]

Waste	Gas generation rate ($1/m^2$/day)
Methanol	8.8×10^5
PCB, aroclor 1242	
liquid	2.1×10^4
6.4 ppm on sand	500
Paperwaste and radioactive solid	0.4
Hexachlorobenzene	
no cover	2.9×10^5
1.9 cm cover	4.1×10^3
30 cm cover	900
Typical wet solid waste landfill ($70\ lb/ft^3$)	12.9 to 25.2

Impounded solids may react with closure cover materials. A detailed listing of the general types of materials that may produce gaseous emissions upon impoundment closure are published in the Federal Register as EPA's proposed rules (Vol. 43, No. 243, December 18, 1978, Appendix I). Classifications of sludges that are acid-forming (i.e., sulfides), oxidizing or reducing, fume or vapor forming, and exothermic have been listed by Curry.[58]

Impoundment operators must consider gas-forming reactions that may occur either during or subsequent to site closure. This can best be identified by impoundment content and subsoil characterization during a site survey or from an inventory list. Cover materials can affect gas generation as well as control its emission. This includes:

- Control of air transfer (causing less aerobic conditions)
- Possible reduction of infiltrate
- Affect on character of infiltrate
- Reactivity of the cover material (regulations specifically prohibit adding wastes that react with cover material)
- Possible concentration of reactive gases produced beneath the cover

The central consideration of whether to remove the residual waste contents of the impoundment and to what depth or extent should be based partially on probable gas problems. Therefore, a brief discussion of the mechanisms of gas emission upon closure of impoundments is presented.

Gases Released from Surface Impoundments Upon Closure

The proper management of SI closure to minimize venting of toxic, explosive, or reactive gases includes considerations to preclude further gas generation and venting of existing gases. Such emissions will affect subsequent site use especially for uses involving buildings and extended exposure uses. Venting of gases can occur during three phases of the impoundment closure:

- While the impoundment material remains uncovered and unremoved
- During the impoundment residue removal and cover placement
- After closure

While SI contents remain exposed, a continuous process of volatilization and wetting and drying occurs. These events are affected by local climatological factors such as insolation, precipitation, evaporation, temperature, and surface air transfer (wind). With the site intact, an array of conditions (dewatering, impoundment content fill or draw, chemical and biological reactions, climatological variables) prevent chemical description or prediction of impoundment gas emissions. The most apparent emissions will be vaporization of solvents and volatile organics and venting of biologically generated gases (mainly carbon dioxide, methane, and hydrogen sulfide). The venting mechanism is dependent on vapor pressure and surface exposure and, thus, is only indirectly controllable by impoundment operators.

When discharging, pumping, dredging, or removing impoundment residues, an additional set of gas emission phenomena can occur:

- Liquid surfaces can be renewed and, thus, increase vaporization
- Dried surfaces or crusts can be removed thereby venting entrained gases
- Pressures can be changed and residue components mixed, thereafter affecting gas venting or production

Any decision to remove impoundment residual contents should be based on consideration of gas emissions resulting from the removal process. The natural readsorption or degradation processes of toxic and reactive gases within impounded wastes has encouraged and justified allowing these residues to stabilize and degrade onsite after impoundment use has ceased.[59]

As described in Section 2, the various site closure mechanisms basically involve residue content removal to some depth or no removal, site covering, and protection. Upon impoundment site consolidation and cover placement, gas emission may continue as a management problem requiring venting mechanisms.

Gases produced (or entrained and compressed) beneath covers on impoundment sites will move in various directions due to pressure or by dissolution into moving ground water (or other subsurface liquids). Although diffusion is the most common gas flow factor, total pressure gradient may become an overriding factor. The latter is often true where mechanical pressure is purposefully applied to remove or disperse gases.

Gas flow within soil is dependent on porosity, free space diffusivity, and the degree of saturation. The rate of diffusion through a porous soil with a degree of saturation, S, is measured by the equation:

$$D_p = 0.66n\, D_o\, (1-S)$$

where

D_p = Diffusivity of wet soil

D_o = Diffusivity at 20°C of free air space

S = Degree of saturation (fraction of void space occupied by water)

n = Porosity of soil

Porosity of soils may vary by a factor of 2 from dense gravel to loose clay. Saturation can vary from a low of 2 or 3 up to 100 percent, greatly affecting gas venting. Diffusivity of individual gas, D_o, is constant (21 ft^2/day for CH_4, and 15 ft^2/day for CO_2). Typical diffusivity values of a gas through a wet covering soil have been demonstrated according to this formula in a study of vaporization and flux of a hazardous chemical waste.[47]

Such diffusivity can be used in the following equation to determine the mass of gas emitted, Q, through a soil layer with time:

$$Q = D_p\, A\, Co/L$$

where

L = Soil layer thickness (feet)

A = Soil layer area (square feet)

Co = Gas concentration differences across the soil layer

This mass rate movement of gas is based on diffusion induced by gas concentration. Any movement caused by external or internal induced pressure would be additional.

3.7.2 Fugitive Dust Emissions

Particulate air emissions can be generated during the operation, closure, and post-closure use of SI's. The generation and dispersion of dust from a hazardous waste disposal site is of concern because of its potential health hazard characteristics as well as its adverse visibility effects. In recent years, considerable attention has been focused on the problem of fugitive dust, since many air quality control regions have not met the ambient air standards for particulate matter. In many cases, the cause of nonattainment has been identified as fugitive dust.

Causes and Sources of Dust

Fugitive dust emissions consist of particulate matter that may become airborne due to the forces of wind, human activity, or both. During closure and post-closure use of SI's, dust emissions may be caused by:

- Wind erosion of the waste materials
- Reentrainment of particulate matter by vehicular traffic on haul roads and exposed surfaces
- Excavation of waste materials during closure
- Wind erosion of the cover soil

The fugitive emissions produced by wind erosion of SI stored wastes depend on the waste type, moisture content, wind velocity, and surface geometry. Although many equations have been developed by researchers in estimating emissions generated from agricultural soils, there seems to be a basic agreement that between 2.5 and 10 percent of all the soil eroded due to wind becomes airborne as suspendable particulate matter.[60] It can be assumed that a similar value would be applicable to SI wastes.

Fugitive dust emissions from unpaved surfaces caused by vehicular traffic on exposed waste surfaces and haul roads are affected by the surface texture of the road, road material, surface moisture, vehicle speed, and type. Fugitive emissions from unpaved surfaces can be estimated using emission factors developed in EPA Publication AP-42, "Compilation of Emission Factors," if the silt content of the surface materials (percentage of weight of particles smaller than 75 micrometers in diameter), average vehicle speed, and average daily traffic are known. Dust emissions from unpaved surfaces generally exhibit a particle size distribution of 60 percent of the particles below 30 micrometers in diameter.[61] Fugitive dust emissions from SI closure operations involving waste removal are mainly due to excavation, vehicle and equipment operation, and wind erosion of the exposed waste surfaces. Although waste removal should be of a short duration, excavation activities can be a major source of dust emissions. The exposed waste surfaces are susceptible to wind erosion and to the mechanical movement processes of the excavation equipment. Dust emissions are affected by the amount of excavation activity and weather conditions. The dust generated from the mechanical movement processes, as in the case of waste excavation, is generally insensitive to the ambient wind speed. Wind speed does determine the drift distance of large dust particles and, therefore, the localized impact of the fugitive dust source.

Upon completion of the closure procedures, the SI site will be covered with a soil layer that may act as a source of fugitive dust if not properly constructed. Wind erosion of this soil will result in particulate emissions. The quantity and characteristics of these emissions are dependent on soil type, moisture content, wind velocity, and surface geometry. Cover design features along with procedures that can be employed to minimize fugitive dust emissions are discussed in Section 4.9.

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SECTION 4

TECHNICAL CRITERIA FOR IMPLEMENTATION OF CLOSURE PROCEDURES

The alternatives that must be considered during closure of an SI are shown schematically in Figure 4-1. The order of issues in Figure 4-1 may not be completely correct for every situation. Furthermore, many issues are interrelated to a degree that they cannot be accommodated in a generalized procedure. Therefore, a thorough understanding of all technical criteria is fundamental to selection of an environmentally sound closure procedure. This section presents the detailed technical criteria for closure based on a generalized procedure.

Dewatering of the impoundment is usually the first step in the procedure to permanently close an SI. The next issue is whether the site will be decontaminated by removal of residual waste sediments or whether the residual waste sediments will be left onsite. In the extreme case, site decontamination would involve removal and offsite disposal of all residual waste sludges, liner materials, and any contaminated soils. Surface soils contaminated by spillage must be considered as well as subsurface soils contaminated by leakage. Partial decontamination is also possible. In this case, portions of the sludge, liner, and underlying soils could be removed.

In the event that site geology and geography minimize waste migration, leaving the residual waste solids onsite in an engineered closure may be the most practical, cost-effective, and environmentally sound alternative available. The physical and geohydrological integrity of the site combined with the physical condition of any liners, dikes, or water balance controls necessary to ensure the requisite integrity of the site must be considered in detail. Methods of sludge consolidation, dike rehabilitation, backfill, and cover are all crucial to the long-term stability of the surface of the closed impoundment.

The choice of in situ versus offsite sediment disposal must be made after careful consideration of the following criteria. If the SI was a technical and environmental success and these conditions can be maintained after closure with a minimum of facility maintenance, closure of the site with residual sediments in place may be an acceptable alternative. If the waste sediments are particularly hazardous, overall environmental impacts may be minimized by in situ disposal in a properly engineered fill and closure operation. Excavation of the sediment with transport to an active disposal site may merely postpone the question of ultimate disposal of the waste sediment and increase the risk of public exposure during excavation and transport. Unless the waste can be destroyed or treated to render it chemically inert and/or

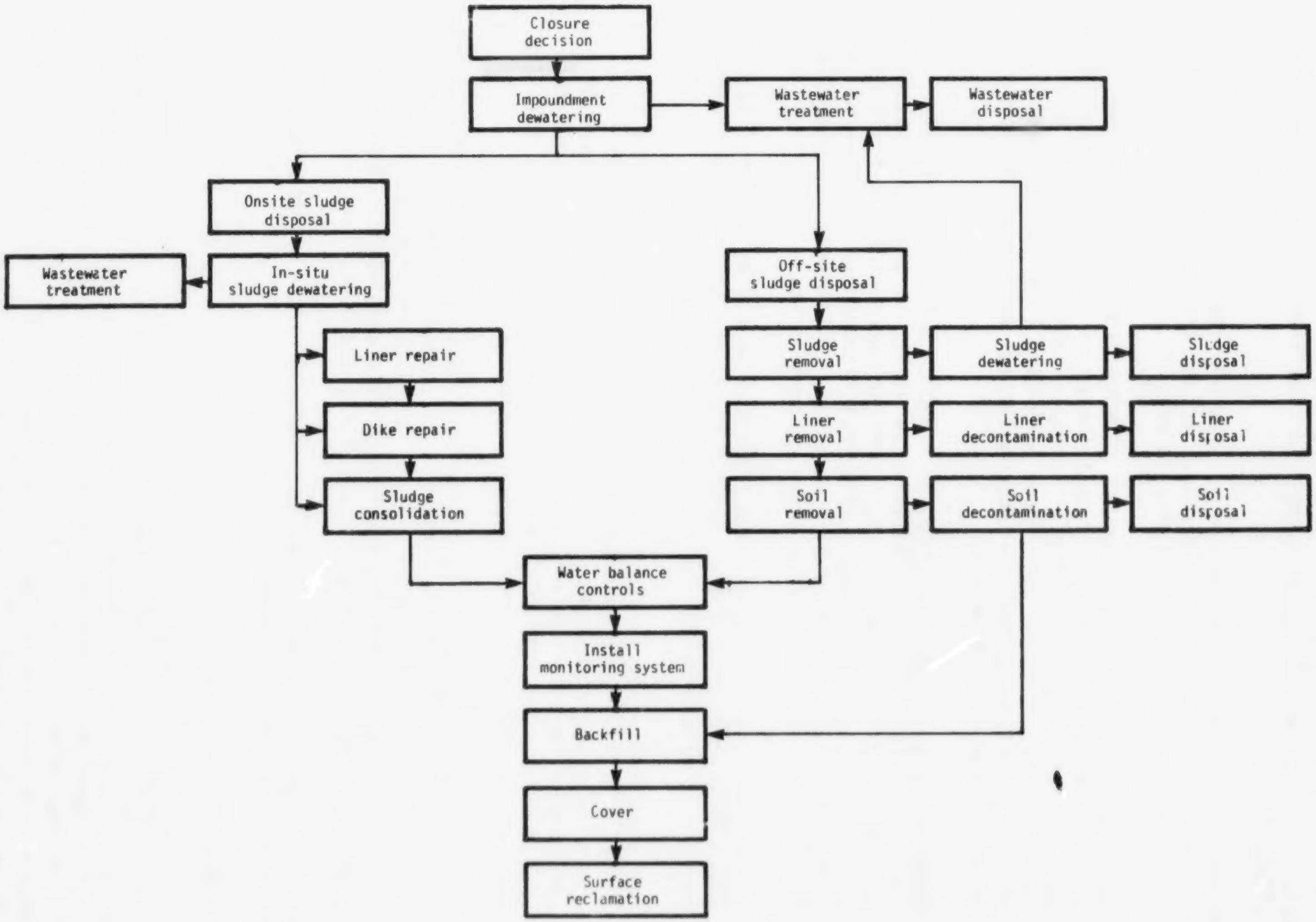
Closure decision
Impoundment dewatering
Wastewater treatment
Wastewater disposal
Onsite sludge disposal
In-situ sludge dewatering
Wastewater treatment
Liner repair
Dike repair
Sludge consolidation
Off-site sludge disposal
Sludge removal
Sludge dewatering
Sludge disposal
Liner removal
Liner decontamination
Liner disposal
Soil removal
Soil decontamination
Soil disposal
Water balance controls
Install monitoring system
Backfill
Cover
Surface reclamation

Figure 4-1. Surface Impoundment Closure Key Steps

nontoxic, in situ disposal should be fully evaluated. If the waste sediment is extremely hazardous and of large volume, in situ disposal may be the only feasible alternative.

Guidelines for selecting the method of site decontamination are necessarily vague since many of the technical issues are waste specific and/or site specific. However, some useful criteria are:

- Waste characteristics -- Since the closure procedure is designed to promote the safe and permanent containment of hazardous wastes, waste characteristics are necessary criteria to consider. These characteristics include the degree of hazard (i.e., corrosive, reactive, ignitable, toxic, bioaccumulative, mutagenic) and the potential for waste migration.

- Geohydrological characteristics -- A decision to leave either residual waste sediments, contaminated soils, or any other source of soluble contaminants onsite should not be made without a thorough geohydrological field study. This investigation will reveal the site geohydrological characteristics necessary to evaluate the potential for ground water and surface water contamination.

- Post-closure use -- The closure procedure should be designed to be consistent with the proposed site end uses and promote the permanent conversion of the wastes to a stable nonhazardous state.

- Minimum maintenance -- The closure method should be designed to minimize post-closure maintenance if at all possible. Such maintenance would include collection, treatment, and disposal of effluents from water balance control processes (runoff, leachates, ground water, etc.) as well as the repair of cover, dikes, surface drainage ditches, or other physical features.

- Environmental impacts -- Selection of a closure plan should take into account the public health risks and environmental impacts (both onsite and offsite) of each step of the closure process. These evaluations should include the feasibility and impacts associated with waste removal, transport, and final disposal.

More specific criteria regarding individual steps of the closure process are discussed in the following sections.

4.1 IMPOUNDMENT DEWATERING

The first step in the closure procedure usually involves the removal and disposal of standing liquid. This liquid generally occurs as a layer above the waste solids and is comparatively free of suspended solids. Removal of this liquid is necessary before the residual solids can be removed or before sediments are dewatered. There are various methods for removing this aqueous waste; several are described below. These liquids will probably be hazardous and should be handled accordingly. Disposal should also be according to appropriate federal, state, and local regulations.

- Decanting -- Liquids within or ponded on the surface of the impoundment can be removed by gravity flow or pumping to a treatment facility if there is not a large percentage of settlable solids.

- Pumping and settling -- Liquids or slurries composed of suspended or partially suspended solids can be removed by pumping into a lined settling pond and then decanting. Sludges are disposed in a dry state, and either returned to the impoundment or disposed in another contained site.

- Solar drying -- Disposal of the liquid in a climate suitable to evaporation is another technique and could be subject to air emission regulations. Sludges remaining after evaporation are left in the impoundment or disposed in another contained site. Volatile organics should not be handled in this manner.

- Infiltration -- Certain aqueous waste can be handled by infiltration through soil provided the hazardous substances are removed by either soil attenuation or underdrain collection of the solute. Collected solutes are usually treated.

- Process reuse -- Some aqueous waste can be recycled in the manufacturing process a number of times until the contaminants are at a level requiring disposal by one of the methods previously mentioned. Reuse does not dispose of the waste but can significantly reduce the quantities to be disposed.

- Chemical neutralization -- Aqueous waste with low levels of hazardous constituents frequently lends itself to chemical neutralization and subsequent normal discharge under NPDES permit requirements.

- Absorbants -- Materials can be added to aqueous impounded wastes to absorb free liquids. Absorbants include sawdust, wood shavings, agricultural wastes such as straw, rice and peanut hulls, and commercially available sorbents.

4.2 WASTE SEDIMENT AND SOIL REMOVAL

If it is determined that an SI will be best closed by removing the waste residuals, the removal procedure must be selected so that adverse environmental impacts are minimized. The alternate removal procedures fall into two general categories -- wet or dry method.

4.2.1 Wet Methods for Sediment Removal

These techniques are based on removing the sediment as a slurry. They are convenient and inexpensive as long as the slurry produced can be transported and disposed in slurry form. Removal of waste sediment under a water blanket is an excellent way to minimize odor and/or waste oxidation reactions that might occur upon contact with the atmosphere. Wet methods of waste removal generally provide the fastest closure schedule since time for sediment drying is not necessary prior to its removal from the impoundment.

- Resuspension -- Dewatering of the SI is stopped when the remaining water volume is the minimum necessary to transport the sediment as a pumpable slurry. Either an air jet or a water jet* can be used to resuspend the sediment. A vacuum tank truck with internal mining capability is recommended for pumping the slurry from the impoundment.

- Excavation -- If the sediments have hardened or formed a plastic mass that will not flow freely and resuspend, excavation is the only alternative. Sediments that have solidified may be excavated with a high-pressure water or air jet from a floating platform. However, the simplest technique is to use a high-speed rotary cutter mounted at the suction of a pump with the entire assembly hung from a floating platform. Such devices are typically used to mine clays underwater and are commercially available.

Plastic or semisolid sediments will probably have to be excavated by clamshell bucket or some other mechanical digging operation. Unless a water blanket is necessary for odor or gas control, this is best done with a minimum of water remaining in the impoundment.

4.2.2 Dry Methods for Sediment Removal

These techniques require that the fill water in the sediment be removed by evaporation. They have the advantage of no wastewater problem at the disposal site, and the sediment can be disposed as a dry solid. The disadvantage is that a long period of time may be required to air dry specific sediments in certain climates. Thick sediment deposits may require removal in layers. Environmental concerns are sediment exposure to the atmosphere and sediment dusting during excavation. (See Section 3.7 for air emissions considerations.)

- Vacuum transport -- This technique works only with powdery sediments or sediments that can be converted to powder or granular form by plowing, disking, or other techniques. Vacuum transport minimizes dust problems; however, if sediment disking is necessary, the dust problems are maximized.

- Excavation -- These techniques are best suited to hard, solidified sediments that need some type of mechanical breakdown to produce conveniently handled pieces. Frequently, the excavation process produces severe dust problems that have to be controlled by water sprays. Any dry excavation process will produce some dust and pose a potential health hazard to excavation equipment operators. Samples of the residual sediments should be subjected to chemical and toxicology studies to determine potential health hazards before dry excavation is selected. Excavation can be by drag line from the perimeter of the impoundment or by front end loader or bulldozer operations inside the impoundment. Covered conveyors can be used to transport sediment from the impoundment bottom to truck loading facilities outside the impoundment if truck access to the inside of the impoundment is impractical or hazardous. Excavation operations involving freefall of the sediments or extended airborne transfers such as clamshell buckets, power shovels, etc. should be avoided because of spill and dust problems. If possible, all operations should be carried out inside the impoundment to minimize surface contamination through spillage.

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*If a water jet is used, impoundment water should be the water source.

4.2.3 Liner Preservation

The impact of the waste removal process on the integrity of the impoundment liner is of vital concern. If a wet excavation process is used, liner integrity must be preserved throughout the entire sediment removal process. Even if highly effective leachate collection systems are in operation, major liner failures will result in large-scale contamination of the surrounding soils and must be avoided.

Where dry excavation processes are used, the possibility of water accumulation from rainfall exists and liner integrity must be maintained to the greatest extent possible. Scheduling of the excavation process to confine excavation operations to small areas that can be cleaned up and diked off to prevent rainfall runoff from the remaining sediments to excavated areas is recommended.

4.2.4 Soil Removal

Excavation of contaminated surface soils, soils underlying liners, and dike soils is easily accomplished by normal excavation methods. Disposal of the contaminated soils, however, is less straightforward and can be expensive if disposal as a hazardous waste is required. Onsite disposal of all contaminated soils within the impoundment site should be considered. Sealing of contaminated soils in the impoundment via a landfill type closure process may be a cost-effective and environmentally sound alternative to offsite hauling and disposal. Excavation of deep soil strata is expensive and the volumes of soil involved may be very large. Every consideration should be given to soil decontamination by controlled leaching programs in preference to excavation.

4.3 SEDIMENT DEWATERING

The reasons for dewatering the residual sediments are highly specific to the site, the waste itself, and the method of ultimate disposal of the solids. The feasible alternative methods of dewatering are specific to the site, the sediment characteristics, and the degree of dryness required.

EPA guidelines for SI closure require that if residual wastes are left in the impoundment, these wastes must have the consistency of nonflowable solids. Generally, this must be done by removing water, although chemical fixation (see Section 4.7.3) may also be required.

If the sediments are to be transported offsite for ultimate disposal and wet excavation methods are to be used, it may be cost effective to dewater the solids prior to transport to reduce volume and/or produce a nonflowable solid for land disposal at the new site.

Passive dewatering is confined to those methods where no mechanical energy input is directly applied to the removal of water. In an SI, the only operative passive methods are solar evaporation and drainage caused by gravity or capillary forces. Active dewatering consists of those processes where thermal energy (drying) and/or mechanical energy (filtration) is used to remove water from the solids.

4.3.1 Passive Dewatering

The feasibility of passive dewatering is the evaporation potential at the site. The evaporation potential is the maximum evaporation that can be expected under ideal conditions and is defined as the difference between the normal annual Class A pan evaporation rate and the average annual precipitation. The evaporation potential is a very strong function of regional climate and site exposure to wind and sun. Two extremes within the continental U.S. are the Pacific Northwest Coast and the Sonora Desert as shown in Table 4-1.[8] Similar calculations can be made for most locations in the U.S., but local knowledge and/or data are required to adapt regional data to specific sites since annual precipitation and sunshine days can vary widely between areas only short distances apart.

It must be remembered that the evaporation potential is the maximum evaporation that can be obtained from a liquid surface under ideal conditions. It can be used to determine if solar evaporation is a significant mechanism, but it is not the rate at which moist solids will dry. The drying rate is controlled by the rate of moisture migration to the surface of the sediment particles by diffusion from within the particles and capillary

Table 4-1. Evaporation Potential Variations[8]

Region	Annual condition (inches of water)		
	Class A pan evaporation	Average precipitation	Evaporation potential
Pacific Northwest Coast	30	100	-70
Sonora Desert	140	5	136

tension from below the sediment surface layer. Therefore, only a function of the Class A pan evaporation rate can be expected at an SI site.

The second passive dewatering mechanism is draining of water from the voids between sediment particles. This mechanism is only significant if the sediment is free-draining and there is a means of removing the drainage water from the interface between the sediment and liner.

Both passive dewatering mechanisms can be significantly enhanced by various forms of physical assistance. Evaporation can be significantly accelerated by keeping the sediment layer thin and the waste solid surfaces at maximum moisture content. This can be done by dividing the impoundment into three areas: (1) sediment storage, (2) sediment drying, and (3) draining water sump. Using this technique, the sediment is bulldozed or otherwise transported to the storage area where it is stockpiled to a considerable depth. The stockpile area should be drained to a sump so that the maximum free drainage can be realized as a result of the depth of the sediment stockpile. Sediment from the top of the stockpile should be placed in the drying area in thin layers. When dry, the sediment can be either stockpiled in a separate storage area or covered with another layer of sediment.

If the impoundment is too small in surface area to allow an in situ drying program, sediment drying beds can be constructed outside the impoundment. However, containment of all sediment drying operations within the impoundment itself is highly recommended to minimize surface contamination via spillage and wind drift.

If thin sediment layers cannot be provided, an alternative is to disk or otherwise plow the sediment to break up the surface crust, turn under dried material, and expose moist solids. This is not practical with a synthetic film liner.

The evaporation of water requires a net heat input to the sediment. Generally, solar radiation is the only cost-effective source of thermal energy. Modifications of the adsorptivity of the sediment by addition of carbon black is possible but has to be tested. Crushed coral and sawdust have been used for restricted moisture adsorption. Protection of the sediment from incident precipitation is desirable in areas where precipitation occurs on a year-round basis and the evaporation potential is not high. Plastic films are expedient for small surface areas but disposal of the contaminated plastic film may be a serious problem.

4.3.2 Active Dewatering

To implement either a mechanical dewatering or thermal drying operation, it is necessary to remove the sediment from the impoundment or at least stockpile the sediment in a diked storage area to clear a processing area within the impoundment itself. The latter alternative is preferred to prevent surface contamination around the impoundment.

Mechanical dewatering processes will produce a nonflowable filter cake suitable for landfill disposal within the impoundment or at some other hazardous waste disposal site. The filter press is the most effective unit. The filtrate may be disposed of in the same manner as the aqueous phase that was removed when the impoundment was dewatered. However, the filtrate may be of higher strength than the impoundment water and require special handling. It also may be further contaminated by solids conditioning chemicals or oils that do not completely remain with the solid fraction.

It must be remembered that not all sediment sludges can be filtered to the extent necessary to produce a nonflowable solid. Chemical conditioners or polymers may have to be added to the sediment sludge to obtain the desired results. Uniform filter performance is unlikely if the impoundment was used for the disposal of more than one waste since sediment properties and physical characteristics will not be uniform.

Thermal drying has advantages; no filtrate is produced, and all of the contaminants are converted to dry solids. However, there is a very high probability that thermal drying will create a significant air emissions problem. It is also energy intensive. Unless the sludge volumes are very large, onsite thermal drying will not be cost effective if at all feasible. The thermal stability of the sediments is the key to technical feasibility. A reactive or easily decomposed material may produce a toxic or otherwise hazardous gas.

4.4 LINER REMOVAL/REPAIR

Post-closure use of impoundment liners, whether of clay or artificial material, is an integral part of site closure. The necessity of repair or possibility of removal are dependent on waste disposal site, liner condition, and site-specific factors.

4.4.1 Reason for Removal

The liner can be removed only if the waste sediments are removed for offsite disposal, in which case the site can be backfilled and returned to any suitable use. Removal of the liner is recommended under these conditions to avoid creation of an artificial subsurface water reservoir that could affect the surface load bearing capability of the soil.

If significant contamination of subsurface soils has occurred, an argument can be made for leaving the liner in place to minimize leaching of the contaminated strata by percolation of surface water that might eventually reach the ground water system or surface water system. In the general case, significant soil contamination would not be the rule with lined impoundments unless the reason for closure was massive failure of the liner. Thus for the case of permitted impoundments that will have residual sediments moved to offsite disposal, liner removal is recommended.

4.4.2 Liner Removal Methods

Clay or other impermeable soil liners can be removed entirely by normal excavation methods. Liner removal should follow and be separate from sediment removal to minimize contamination of the underlying soils. If the clay or soil liner is relatively thick and it is possible to excavate only a few inches off the surface of the liner, the remaining liner material could be broken up and mixed with the underlying soil and/or backfill material to minimize transport and offsite disposal.

Liners made of synthetic materials such as Hypalon, PVC, etc., should be taken up in much the same manner as they were installed. Convenience of handling and disposal should control the width of the individual sections.

Hard surface liners such as gunnite or concrete should be broken up by normal mechanical means and, depending upon forecast post-closure use, either removed or left in place in a rubble form.

4.4.3 Reason for Liner Repair

In the event that waste sediments are to be left in situ and the site closed as a landfill, the physical condition of the liner is a significant concern. The choice between liner repair or liner replacement depends on the age and condition of the liner material, estimated service life of the liner in contact with the waste sediment, the physical and chemical characteristics of the sediment, and the probability of success of the water balance controls (i.e., cover impermeability, ground water diversion, etc.).

In general, liners made of clay or impermeable soils are suitable for buried service as long as ground fractures due to seismic activity are not a problem. Synthetic liners provide flexibility for limited ground movement but have unknown long-term service lives in a buried environment. Hard surface liners such as gypsum or concrete may have problems due to ground movement or excessive overburden stress.

4.4.4 Liner Repair Methods

Clay or soil liners are easily repaired but must be considered contaminated and may pose health and safety hazards for workers. Synthetic and hard surface liners may be washed clean prior to repair but repairs are more difficult to effect. The strength and seal of repairs to hard surface liners will always be questionable. Liner construction and repair methods are described in references 1 and 2.

4.5 SOIL CONTAMINATION TESTING

In the event that contamination of the subsurface soils is suspected, a field sampling program will be necessary to confirm the type and extent of soil and ground water pollution. Fortunately, the same sampling and analysis program will also provide supplemental data on soil strata by type and depth and local data on ground water conditions.

If soil contamination is confined to local areas near liner failures, soil excavation and offsite disposal may be feasible, cost effective, and desirable. If soil contamination is general throughout the site and/or extends offsite via a ground water plume, extensive water balance control measures, as described in Section 4.8, may be necessary.

4.5.1 Surface Soils

Contamination of surface soils surrounding the impoundment is a function of past operating practices. Overfilling leads to wind driven waves overflowing the edges of the impoundment. Spillage from waste discharge operations, truck transport, sediment removal, etc., are all sources of surface contamination in the general vicinity of the impoundment. Discolored soils, lack of vegetation, dead vegetation, and discolored rainwater runoff are all clues to surface and near surface contamination. Random samples of surface soils (top 3 to 6 inches) should be taken in areas of suspected contamination and analyzed for probable contaminant species.[3] (See also Section 4.5.6.)

4.5.2 Soils Adjacent to Impoundment

The soils that underlie the impoundment and line and form the dikes generally will contain some small amount of contamination. The impoundment that has never had a liner failure of any type is rare. Impoundments that have a liner constructed of a low permeability soil or of a clay will, if the impoundment is old enough, show some trace of contamination as a result of slow seepage.

If the residual sediments are to be taken offsite for disposal and the liner removed, random samples of the underlying soils should be taken and analyzed for probable contaminant species. If the liner is to be left onsite but not intact, the liner should be inspected for possible failure areas, portions removed, and the underlying soils sampled. Dikes can be cored and the samples analyzed.

4.5.3 Soils Remote from Impoundment

If a major failure of the liner occurs, large quantities of contaminated water may infiltrate the underlying soils, reach a ground water aquifer, and be transported away from the impoundment or at least away from the point of liner failure. The areal extent of this large-scale contamination of subsurface soils will be controlled by the rate of water transport and the absorptive capacity of the soils for each of the contaminants.

If properly located, ground water monitoring wells will allow for the detection of this contamination and these data may well be the reason for site closure. However, definition of the areal extent, and depth and thickness of the plume of contaminated ground water and soil generally require a relatively detailed geohydrological field study.

If the contamination has significantly changed the electrical conductivity of the contaminated ground water and soils, a surface resistivity study provides a rapid and cost-effective semiquantitative determination of the areal extent of the contaminant plume. Depth of contamination is less precisely determined. The results of the surface resistivity study can be used to plan the most cost-effective drilling and sampling program. Such a program is essential to completely define the impacted areas, the type of contamination, the concentrations, and the leachability of the impacted soils.

4.5.4 Drilling and Sampling Programs

The objective of the geohydrological study is to identify the following parameters:

- Extent of soil contamination
- Extent of ground water contamination
- Potential for contaminant migration
- Location of local ground water and surface water flows relative to contaminant plume

A geotechnical consultant with prior experience in subsurface pollution control should plan and direct the study. A key to identification of contamination is to obtain background or reference samples of local soils and ground waters known to be free from contamination. Soil and ground water samples must be collected and stored to minimize contamination and physical and chemical degradation of the samples.[4-7]

4.5.5 Ground Water Analysis

Water analyses can be divided into two types, screening and qualitative identification. Certain basic parameters are indicative of contamination without identifying the type and concentration of specific contaminants. These parameters must be measured in uncontaminated samples and compared to the results for suspected samples. Some of these parameters include:

- TOC -- Indicator of organic chemicals
- Conductivity -- Indicator of soluble ions
- pH -- Indicator of acidic or basic waters
- COD -- Indicator of chemically oxidizable organic and inorganic materials
- Oil and grease -- Indicator of petroleum oils

Other indicators of groups and classes of contaminants exist but must be detected by a component chemist on a case-by-case basis.

The standard methods of analytical chemistry are available for identifying specific contaminant classes on a qualitative and quantitative basis. Analytical procedures for quantitative determinations of specific organic and inorganic materials is a rapidly evolving state of the art.[8-10] Analytical determinations are generally expensive, thus, the utility of such data and the impact of the result on the decision making process must be carefully considered during design of the sampling and analysis program.[4,11,12]

4.5.6 Soil Analysis

There are three types of analyses of interest in soil characterization: (1) soil properties, (2) leachable soil contaminants, and (3) exchangeable soil contaminants. Soil property analyses should be performed only in the event that geohydrological estimates of lateral and vertical migration of contaminated water are necessary. Types of analyses, methods, etc. are discussed in references 13, 14, and 15. Generally, the major variables such as pH, cation exchange capacity, organic matter content, and permeability are considered in this group of analyses.

Leachable soil contaminants analyses identify the types and amounts of contaminants that can be released to uncontaminated ground water from the soils. Types, methods, and interpretation are discussed in section 3.1. Basically, extraction (or leaching) methodology is designed to determine the potential mobility of specific compounds identified early in the investigation.

Exchangeable soil contaminants analyses identify the types and amounts of contaminants that can be stored and/or released by soils via ion exchange interactions with ions in ground water. Types, methods, and interpretation are discussed in references 16 through 19. These analyses assist in detailing the chemistry of specific solutes in the existing soil environment.

4.5.7 Interpretation of Results

The identification of one or more contaminants in either soil or ground water is not conclusive evidence of a significant pollution problem. Results of sampling and analysis programs must be interpreted from the geohydrological point of view in terms of contaminant mobility, ultimate fate, long-term soil-water interactions, etc. It is important, however, that the general chemistry of the soil environment and of the contaminants in question be known so that general conclusions regarding potential mobility can be made.

Given the rapidly developing state of the art in sampling and analyses combined with the complexity of geohydrology, absolute conclusions are difficult to prove. All results must be viewed from a soil-water systems perspective.

4.6 DIKE STABILITY

Dikes are used as part of SI structures that are partially or completely aboveground. A decision to close a diked impoundment as a landfill containing water sediments is dependent upon an analysis of the structural integrity of the dikes and the dike-soil system. Of particular interest is the ability of the dike to withstand the loads imposed by the backfill and cover material, particularly under conditions of water saturation of the backfill, cover, and dikes.

Evaluation and surveillance of dike stability is necessary to avoid environmental, property, and human damage due to failure of the impounding structure. Elements to be considered in the evaluation of dike stability include foundation conditions, embankment materials, liner type, and waste material, all of which are part of the dike system. The condition and stability of the dike system is constantly changing. Long-term effects of various external factors such as frost, wind, rain, and temperature as well as man, animals, and vegetation should also be considered. Therefore, periodic inspection and reevaluation is required to assure stability of the dike system in the future.

Several phases are involved in the evaluation of dike stability. The initial phase is a compilation and review of available geotechnical and construction data. This is followed by a field reconnaisance of the site to examine present conditions. Depending upon the results of these phases, additional technical investigations may be necessary. An evaluation of the stability of the dike system is then made from the compiled data. If the dike is considered to be unstable, then recommendations should be made to either repair or remove the structure. If the dike is considered to be stable, a plan for future surveillance and monitoring should be recommended.

The following sections discuss more detailed guidelines for evaluating the stability of the dike system. Rigid guidelines and standards cannot be established for every conceivable site condition. The analysis of dike stability must be site-specific and will require not only a systematic technical approach but also considerable judgement by experienced engineers.

4.6.1 Inventory of Historical Information

The initial phase in investigating the stability of the dike system is an inventory and compilation of all existing information. The purpose of the inventory is to review what is known and to identify what is unknown about factors that affect the stability of the dike system.

A location plan (i.e., USGS quadrangle sheet) should be obtained showing the impoundment facility with respect to existing physical and topographical features. Also, a failure impact zone can be shown on the location plan based on an assumed failure of the dike. Next, an accurate site map needs to be obtained (preferably 1 inch = 40-foot scale -- 2-foot contour interval) showing specific site conditions including utilities, structures, wells, geotechnical instrumentation, borings, test pits, bedrock outcrops, springs, trees, and topographic features.

The as-built construction plans and specifications for the impoundment facility can also be assembled together with all photographs, inspection reports, and construction records. Quality control measurements such as compaction tests, in-place density tests, moisture contents, grain size analyses and soil test data should be compiled. In addition, all geotechnical information such as geotechnical reports, logs of test borings and test pits, soil test results, surficial and bedrock maps, aerial photographs, seismic surveys, results of instrumentation, and related information should be evaluated.

Based on the accumulated information, typical and critical cross sections of the dike system can be developed showing soil and bedrock units, ground water levels, and other geotechnical and construction information. Test results on the foundation soils and embankment materials should be catalogued and cross-referenced to the soil profiles.

4.6.2 Reconnaissance Investigations

The reconnaissance investigation phase consists of a detailed site inspection by a team of personnel experienced in the fields of engineering geology, soils engineering, structural engineering, and dike design and construction. The purpose of the field reconnaisance is to examine actual conditions at the site, verify the existing data, and identify any signs of dike instability.

A detailed visual inspection should be conducted preferably during times when vegetation is minimal and snow cover is gone. The inspection will identify features that indicate potential instability of the dike such as seepage, settlement, cracking, bulging, sinkholes, surface erosion, growth of vegetation, slumping or undercutting of the toe, and animal burrows. Typical inspection checklists are shown in references 20 and 21. Photographs of all pertinent features should be taken. The field inspection should also include survey measurements to verify site and topographic data shown on the site plan. Monitoring of all geotechnical instrumentation can also be completed during the inspection. Areas of seepage and leakage should be carefully examined, the flowrates recorded, and samples of the effluent obtained.

4.6.3 Geotechnical Investigations

Subsequent to the inventory and reconnaissance phases, the compiled data can then be reviewed to determine whether additional geotechnical investigations are needed to evaluate the stability of the dike system. Further subsurface investigations may be necessary to determine types of foundation and embankment materials, obtain soil and rock samples for laboratory testing, install geotechnical instrumentation such as ground water observation wells and piezometers, conduct in situ testing, and perform laboratory tests. The scope of the investigation is dependent on the extent of the available information, the size of the impoundment facility, and the nature and variability of the subsurface conditions. All field and laboratory investigations should be conducted under the supervision of registered professional engineers.

Geophysical methods can be used to determine general subsurface conditions and to determine optimum locations for further exploration. Typical geophysical surveys include seismic refraction, cross-hole seismic surveys, electrical resistivity, gravity, and acoustic monitoring. Direct methods of subsurface exploration include soil and rock borings, auger borings, probes, and test pits. Soil test borings in conjunction with standard penetration tests (ASTM-D-1586) and undisturbed soil samples are the most common procedures for determining subsurface conditions. Classification of soil samples should be in accordance with the Unified Soil Classification System. The spacing, depth, and sampling interval is dictated by the nature and variability of geologic conditions.

A profile of the ground water levels within and at the toe of the embankment is necessary for stability analyses. Ground water observation wells and/or piezometers should be installed and measured not only during the exploration phase but also indefinitely thereafter. The elevation of the observation wells and piezometers will depend on subsurface conditions, present and future ground water levels, and the number of aquifers within depths significant to the facility.

In situ field testing such as vane shear tests, cone penetrometor tests, pressuremeter tests, and permeability or pumping tests may be used to further define specific characteristics of the foundation or embankment materials. Laboratory testing to determine engineering parameters of soil samples is carried out for two purposes:

- Classification of the soil to identify the type and homogeneity of the various earth materials making up the impounding structure. For instance, these tests would determine whether the impoundment is made of one uniform material or is a zoned embankment composed of two or more different materials.
- Quantitative tests of the various soil types for their engineering parameters. In this case, test results are used in the stability analyses. These tests may include compaction tests, consolidation tests, unconfined compression tests, direct shear tests, triaxial tests, and cyclic-triaxial tests. For example, cyclic-triaxial tests would be conducted to consider the effects of earthquakes on dike stability.

Special soil tests are conducted to help analyze particular soil problems, for example, to identify highly erodible soils known as dispersive clays.[22] These soils have a higher content of dissolved sodium in the pore water than ordinary soils and erode when individual clay particles go into suspension in practically still water. Severe erosion and failure of the embankment slope may occur if saturation of those soils occurs because of leakage from the impoundment facility.

4.6.4 Engineering Criteria

The analysis of stability for the dike system is dependent on numerous variables and assumptions regarding stratification of soil and rock units, physical properties of soil and rock materials, ground water elevations, and predictions of external environmental factors. Accordingly, considerable engineering judgement is required in selecting one of the methods of analysis and factors of safety in the determiniation of dike stability.

Instability of the dike system occurs when a section of the dike mass moves laterally by sliding or by rotation along a circular arc or curved plane. Conventional methods of analysis are outlined in detail in references 23, 24, and 25. The circular arc procedure is generally used for analyzing homegeneous earth dikes founded on deposits of fine-grain material. The sliding block or wedge method is more applicable to stratified deposits of weak soils or inclined zones within the dike section.

Instability of the dike system can also be defined as deformation of the embankment to such an extent that material seeps from the impoundment. This may be due to failure of the lining or fracturing of the embankment materials. Accordingly, the ability of the dike and the liner to yield significantly without functional failure must be considered. Shear strains and deformation of the embankment and foundation soils may develop as a result of settlements caused by loadings due to closure fills and/or future construction.

The analysis of the loading conditions for the dike system must include not only present conditions, but predictions on future loading, ground water elevations, and seepage conditions. The effect of these future conditions must also be reflected in the selection of the shear strength parameters for the soil and rock materials. Recommended minimum factors of safety and corresponding shear strength tests relative to various design conditions are given in reference 23. The final factor of safety to be selected by the engineer should be based on completeness and uniformity of available data, assumptions and predictions regarding future events and loading conditions, and consequences of a failure relative to the environment, property damage, and loss of life.

Seepage pressures as a result of present and future ground water levels in the dike system should be analyzed to determine their effect on slope stability and the potential for piping failures. Information from observation wells and piezometers should be used to evaluate existing conditions. Predictions on future ground water elevations should reflect the most severe seepage conditions likely after closure of the impoundment.

Saturation of the downstream toe or slope may occur as a result of inundation caused by flooding or overflow of nearby drainage facilities. Instability due to saturation and/or sudden drawdown or receding of flood levels must be examined. In addition, erosion and loss of toe support may occur.

Seismic loading due to earthquakes must be included for all impoundment facilities located in zones 1, 2, 3, and 4 as shown in Figures 1, 3, and 4 in Appendix D of reference 20. The extent and type of the analysis will depend on the foundation and embankment soils, location of the facility, and the consequences of failure. Liquefaction of the foundation and embankment soils should be considered when these soils consist of loose to medium density fine sands and silts below the ground water table. A procedure for evaluating the potential for liquefaction is outlined in reference 26.

Certain types of soil, rock, or design conditions related to dike system stability that may require special attention are: Sensitive clays, limestone regions, mined out areas, hydraulic fracturing within the dikes, effect of high temperatures on shear strength of foundation and embankment soils, expansive clays or shales, collapsible soils such as loess, regional settlement, dispersive or highly erodible soils, shrinkage cracks, and formation of ice lenses.

4.6.5 Continued Surveillance

The stability of the dike system is not a static condition. Future loading conditions or environmental events may result in instability or excessive deformation. It is essential that a continuing program of maintenance and technical inspections be implemented immediately after closure of the impoundment. Inspections shall be conducted on an annual basis. Guidelines for periodic inspections are similar to those outlined for reconnaissance investigations. The engineer responsible for the geotechnical investigation and engineering evaluation should determine the inspection program. During the inspections, the geotechnical instrumentation shall be monitored and subsequently evaluated by the engineer.

All maintenance and repair work as recommended by the inspection team shall be implemented immediately thereafter. Particular attention shall be given to the elimination of growth of vegetation and trees on the dike and burrowing animals in the area.

4.7 CONSOLIDATION AND STABILIZATION OF WASTES

A decision to use the impoundment for in situ disposal of the waste sediments will require evaluation of the consolidation potential of the sediments. The objective of this evaluation is to maximize consolidation during the closure process so as to minimize any post-closure consolidation.

A decision to leave the sediments in the impoundment requires that the sediments be dewatered to a nonflowable consistency and that the impoundment be closed as a landfill. Consideration of sediment consolidation during the closure process is necessarily closely coupled to the dewatering of the sediment, and Section 4.3 should be reviewed prior to reading of this section. This section will consider both consolidation of flowable sludges, slurries, and solids during the closure process, and nonflowable solids during the post-closure period. This section does not consider the consolidation of either the base soils underlying the impoundment or consolidation of the rockfill and cover material.

The consolidation problems anticipated during closure of an impoundment will be highly specific to impoundment geometry, sediment depth, and the physical and chemical properties of the sediment. These difficulties may be compounded by the fact that more than one type of sediment may be present in the impoundment. The problem of heterogeneous sediments can be handled by area segregation within the impoundment or by sediment homogenization.

For discussion purposes, waste sediments will be classified in terms of the consistency and bulk handling definitions of Table 4-2.

4.7.1 Consolidation During the Dewatering Process

The reduction of the water content of the sediment that will convert a flowable sediment to a nonflowable solid will simultaneously implement primary consolidation and, to a lesser extent, both secondary and tertiary consolidation. The extent to which consolidation occurs will depend on the sediment properties and the residual moisture content after dewatering. Indeed, the consolidation potential of the sediment as a function of moisture content may be as critical to selection of a target residual moisture content as the requirement to produce a nonflowable solid. Methods for such determinations are discussed later in this section.

Primary Consolidation

It is expected that conversion of the sediment to a nonflowable solid state will effectively eliminate any potential for the occurrence of primary consolidation after closure. However, there are exceptions to every rule, and definition of nonflowable solid is not rigorous. Sediments exhibiting nonNewtonian properties (plasticity, thixotropy, etc.) may tend to entrap water under extreme dewatering pressures and release water at conditions of lower stress. Careful examination of the sediment behavior during exploratory testing of dewatering alternatives is necessary to handle specific problems.

Secondary Consolidation

If the sediments are evaporated to dryness, any potential for secondary consolidation should be eliminated. If evaporation to dryness is not feasible or cost effective, or creates other problems such as a low density, fluffy

Table 4-2. Hazardous Waste Consistency Classifications

Consistency category	Characteristics
1. Liquid waste	<1% suspended solids,[a] pumpable liquid, generally too dilute for sludge dewatering operation.
2. Pumpable waste	<10% suspended solids,[a] pumpable liquid, generally suitable for sludge dewatering.
3. Flowable waste	<10% suspended solids,[a] not pumpable, will flow or release free liquid, will not support heavy equipment, may support high flotation equipment, will undergo extensive primary consolidation.
4. Nonflowable waste	Solid characteristics, will not flow or release free liquids, will support heavy equipment, may be 100% saturated, may undergo primary and secondary consolidation.

[a] Suspended solids ranges are approximate.

solid that must be moisturized and compacted in place to eliminate sediment porosity (permeability), then the potential for volume reduction of solids under expected overburden stress loads should be determined.

Tertiary Consolidation

The potential for reduction of solid mass by dissolution, biological oxidation, and chemical reaction is unique to the sediment and the expected environment in the closed impoundment. The ability to predict tertiary consolidation will depend upon the degree of understanding of the chemical composition of the sediments. Impoundments used for disposal of a limited number of wastes, such as those in single product class industrial plants (oil refineries, fertilizer plants, etc.), are more amenable to such analysis than large, general use impoundments at commercial hazardous waste disposal sites.

4.7.2 Determination of Consolidation Potential

Primary and Secondary Consolidation

The consolidation behavior of a sediment during in situ dewatering by drainage can be determined via a routine consolidation test (ASTM-D-2435). Both the final consolidated volume and the rate of consolidation can be determined. It is important to remember that the scaleup of test results to full-scale operations is dependent on the ability to duplicate test conditions in the field. In situ consolidation of deep sediment deposits will be controlled by factors not measured in the simple consolidation test.

The consolidation behavior of a dewatered sediment experiencing secondary consolidation under an applied overburden stress can also be estimated from ASTM-D-2435 by beginning the test with a sample dried to the same moisture content as proposed for the sediment. To estimate the consolidation behavior of a compacted sediment, the sample should be compacted in the test column before beginning the test.

Tertiary Consolidation

A number of independent mechanisms can contribute to tertiary consolidation. Laboratory tests indicating biological activity and chemical reactions leading to consolidation are discussed in the following paragraphs. These tests will indicate maximum effects but not the rate at which they may take place. The rates of tertiary consolidation are controlled by the environment within the sealed impoundment. These environmental conditions cannot be duplicated satisfactorily within the laboratory.

Biological

Biological activity is not a direct consolidation mechanism. However, biological oxidation of organics can reduce the total mass of solids by conversion to liquid and gaseous end products. Consolidation of the remaining solids can then occur through conventional physical mechanisms.

The total organic content of waste sediments can be measured by the TOC test. However, this test measures all organics whether biodegradable or not. Nevertheless, the TOC value can be used to estimate the maximum potential for biological consolidation assuming that all the organics are biodegradable. The ultimate biochemical oxygen demand (BOD) test can also be used to indicate the maximum potential for biological consolidation.

A biological consolidation estimate can be calculated by assuming that 1 pound of organic matter will be destroyed for each 2 pounds of oxygen consumed in the BOD test. An assumption regarding the density of the consolidated waste must also be made. An assumption of no density change with biological consolidation is not unreasonable. It must be emphasized that this estimate is probably a maximum value.

Anaerobic conditions exist in many if not most post-closure SI's. The potential for the reduction of the mass of organic matter through anaerobic decomposition is about the same as aerobic decomposition. The potential for generation of noxious odors, flammable gas, and toxic gas is associated with anaerobic decomposition. The rate of anaerobic decomposition is perhaps more sensitive to environmental factors than that of aerobic decomposition. The nutrient balance, the presence of toxic compounds, pH, temperature, and moisture content are some of the factors that can greatly reduce or stop the rate of reaction.

Chemical

The only type of chemical consolidation considered here is chemical conversion of a portion of the waste solids to a dissolved or gaseous product followed by removal with the leachate or release to the atmosphere. Additional chemical consolidation may occur by dissolving solids at one location and reprecipitating them in voids between solid particles. This mechanism is not expected to account for a significant amount of consolidation, however. Testing of the chemical leaching of the waste can indicate the potential for aqueous dissolution of the waste. Test methods are outlined in Section 3.1.

4.7.3 Stabilization of Waste

A number of techniques have been developed for the stabilization of wastes through solidification or encapsulation. The goal of these techniques is to produce a solid, chemically nonreactive material. Some hazardous wastes can be stabilized by these techniques.

Stabilization Technology

Seven major categories of industrial waste stabilization technology were identified in one study.[27] Six of these categories are based on the addition of an agent for solidification or encapsulation. These techniques can produce varying degrees of stabilization, but the volume of waste is increased from 5 to 100 percent. The major categories of waste stabilization are:

- Portland cement-based processes
- Pozzolanic processes
- Thermoplastic techniques (including bitumen, paraffin, and polyethylene incorporation)
- Organic polymer techniques
- Surface encapsulation techniques
- Self-cementing techniques
- Glassification and production of synthetic minerals

Engineering Properties of Stabilized Waste

The available data on the engineering properties of stabilized hazardous waste indicate a wide variation in properties depending upon waste type and stabilization process. One study compared the engineering properties of raw sludge to chemically fixed sludge for five different hazardous waste sludges.[28] One or more of seven different fixation processes were used to fix the sludge.

Chemical fixation is the conversion of a nonsolid waste to a solid form. Fixation is distinguished from stabilization in that stabilization produces a chemically nonreactive waste in addition to one which is in a solid form. Several chemical fixation processes are susceptible to leaching although they may produce a solidified waste high in compressive strength.

Unconfined compressive strength test data indicate that the behavior of fixed sludges in compression is highly process and material dependent. The compressive strengths of sludges fixed by one process were comparable to those of cohesive or cemented soils. Sludges fixed by other processes exhibited compressive strengths resembling low strength soil-cement mixtures. The highest compressive strengths, comparable to low strength concretes, were obtained from four of the fixation processes. Compressive strengths ranged from 0 to 4,500 psi for all tests.[28]

Fixed sludges were generally too hard to be compacted by conventional methods. The 15-blow compaction test (ASTM-D-698) showed very little increase in density with any fixed sludge including those of lowest compressive strength. Results of this test suggest that multiple passes of heavy compaction equipment will be required to achieve any significant increase in density. Moderate compaction may produce a more homogeneous mass of fixed sludge by reducing void space and honeycombing, but the density will not be increased significantly.

The consolidation of fixed sludge is expected to be inversely proportional to the compressive strength. Sludges fixed by most processes are considerably stronger than most soils, and the settlement of the post-closure impoundment would be expected to be because of consolidation of compressive foundation soils.

4.8 CONTROL OF THE WATER BALANCE

In the event that the residual sediments and any other contaminated solids are removed to offsite disposal, closure as a landfill is not required. For this case, water balance controls are generally not required as pollution control measures. In some cases, runoff controls may be justified for erosion control.

If any water soluble contaminants are left onsite or, more specifically, in situ, water balance controls of some type are generally necessary. These controls function to prevent the generation and migration of leachate as a point or nonpoint source into ground water and/or adjacent surface water supplies. Such controls are of two types:

- Water exclusion measures designed to minimize the infiltration of water to the wastes
- Water collection measures designed to minimize the escape of leachate to ground water and/or surface water

It is preferable to concentrate on water exclusion measures to prevent the production of leachate. The incentives are twofold; collection systems typically result in some leakage, therefore, an adverse environmental impact may result. In addition, if leachate is generated and collected, it must somehow be treated and/or disposed in an environmentally safe manner. Treatment of leachate will generally be less cost effective than implementing procedures to prevent its formation.

4.8.1 Need for Control

A systemwide appraisal of all environmental and geohydrological features is required to identify the need for controls and the types of controls that will be most cost effective. If the impoundment has been permitted and all permitting requirements were fulfilled, a geotechnical and hydrological data base adequate for evaluating the need for water balance controls should exist. If this data base is inadequate, some additional field study may be necessary to supplement existing data. This data base should include information about the surface and ground water hydrology, site characteristics, impoundment capacity, and dike characteristics.

Surface Water Hydrology

Factors affecting the occurrence and movement of surface water need to be characterized. Existing data and field investigations should be used to establish the following elements critical to water balance control measures:

- Drainage area
- Topography

- Climatology -- precipitation, temperature, evaporation
- Land use
- Runoff coefficient
- Stream geology -- fluctuation, history, transport of suspended materials, erosion rate
- Surface water quality
- Effect of SI on drainage area (quantity and quality)

Ground Water Hydrology

Factors affecting the occurrence and movement of ground water also need to be characterized. Existing data and field investigations are used to establish the following parameters needed for an understanding of the water balance:

- Water table depth and seasonal fluctuations
- Thickness of aquifer(s)
- Ground water flow direction and rate
- Proximity of water supplies -- public and private
- Ground water quality -- baseline data
- Infiltration rate -- recharge
- Ground water discharge area
- Effects of SI on ground water flow and quality -- presence and location of potential leachate plume

Site Factors

Specific site factors that affect the occurrence and movement of ground and surface water need to be established. Existing data and field investigations are used to study the following site factors as they relate to the water balance:

- Site drainage
- Site soils
  - Vertical and areal distribution
  - Permeability
  - Attenuation capacity
  - Extractable contaminants (leachability)

- Land use (site vicinity)
- Public safety and health hazards
- Relation of SI to drainage

Impoundment Capacity

Impoundment capacity must be known to estimate the retentive capacity of the backfilled impoundment for infiltrating surface water. This allows calculation of overburden stress on dikes and consolidating sediments and estimation of the driving force for leachate migration from the impoundment.

Dike Stability

Water saturation of dikes or high ground water conditions under dikes are two vital factors impacted by water balance controls. Dike stability may be a major incentive for water table and runoff controls.

4.8.2 Surface Water Controls

The primary control measure for excluding water from most impoundments is elimination or minimization of infiltration of surface water. This can be done by a wide range of measures such as:

- Runoff diversion -- Overland flow of runoff over the impoundment cover must be minimized by diversion. This is the first line of defense. The less water reaching the cover means the lower the infiltration potential. In addition to drainage ditches and open channels, structures such as berms, check dams, sedimentation ponds, energy dissipators and dikes can be used to control runoff.
- Surface grading -- The cover itself should be constructed with adequate slopes. This will assure maximum lateral surface runoff and helps to minimize infiltration, which directly affects subsequent enhancement for leachate generation.
- Cover construction -- The cover should be constructed to minimize infiltration
- Revegetation -- Vegetation provides erosion control, and the root system provides a consumptive use for infiltrated water

The importance of surface water controls cannot be overemphasized. Even if the in-place residual sediments are covered by a clay seal, saturation of the backfill above the clay seal must be prevented to minimize hydrostatic stress on the cover and dikes. References 29, 30, 31, 32, and 33 should be consulted for engineering details on the previously mentioned surface water control measures.

4.8.3 Ground Water Controls

Where local geological and hydrological conditions require it, various types of ground water controls can be implemented. The following controls function to prevent the subsurface flow of ground water into the impounded waste.

- Diversion -- Groundwater can be directed around an impoundment site by several means. The effectiveness of diversion is controlled by local soils and the volume of ground water flow. Diversion dams of polymer membranes or sheeting can be effective but will require construction of a high permeability diversion path to guide the accumulated ground water around the site. Slurry-trench cutoff walls or grout curtains can also be used to divert ground water away from a waste site.

- Interception -- Ground water can be intercepted either by wells or collector underdrain systems. Wells require pumping and a discharge point. Depending on regional topography, collector underdrains may also require pumping. Any system depending on pumping has an inherent failure potential and an annual maintenance cost.

- Underdrain systems -- If the impoundment was constructed with a leachate control system, this series of underdrains and/or pump sumps may be suitable for modification to peak shave an occasional high water table. Again, the system will be pump dependent and have a finite failure potential.

4.8.4 Leachate Controls

The last line of defense is to install and maintain a leachate control system. If the impoundment site was originally equipped with leachate controls, retention of this system is required. Special conditions requiring leachate controls to protect ground water quality include:

- Significant soil contamination in and around the site

- Presence of a liner of unknown integrity

- Presence of a stationary reservoir of leachate below the liner resulting from earlier liner failure

- Proximity of usable ground water or surface water resources

The design of leachate control systems is discussed in references 31 and 34. Again, such systems may require pump maintenance and have the additional disadvantage of leachate collection and disposal.

4.8.5 Monitoring

The effectiveness of water balance control measures can be documented by ground water monitoring. The need for a monitoring program would depend on the method of site closure, type of wastes, presence of a leachate plume, presence of contaminated surface waters, proximity of water supplies, and regulatory requirements. A careful analysis of the site hydrogeology should precede the design of a monitoring program. The degree and areal extent of soil, ground water, and surface water contamination must be established before an effective monitoring program can be implemented. Once such investigations have been completed, a site-specific program should be designed.

Monitoring may be either active or passive. Active monitoring systems might consist of one or a series of pumping wells. They are best suited for control of point source contamination to ground water from spills, impoundment overflows, or dike leaks. Conversely, monitoring of leachate is well suited to passive systems. A passive system consists of wells that are not connected to pumps or other monitoring devices strategically located with reference to ground water flow. These wells are sampled at regular intervals to determine changes in concentrations of indicator chemical constituents.

A leachate monitoring system should be designed with the following considerations:

- Monitoring stations -- Wells and surface water points should be established in sufficient number to adequately monitor the movement of acceptable contaminants from an SI to the point of attenuation
- Multilevel monitoring stations -- To sample various depths where thick aquifers or multiple aquifers need to be monitored
- Sampling methods -- May include pumping by suction, compressed gas, submersible pump, or by bailing. Sample containers and preservation techniques must be compatible with analytical goals, especially when trace concentrations of constituents are to be determined.
- Monitoring indicators -- Should be selected to determine the presence and severity of contamination. A water quality baseline should be established by using existing water quality data and/or new data for nearby uncontaminated wells.
- Frequency of sampling -- Must be determined on a site-specific basis and depend on the nature of contaminants and their threat to human health and other environmental considerations
- Length of time -- For monitoring, the flushing out of contamination would depend on ground water flow rates and aquifer coefficients. Monitoring should continue until the baseline condition is approached or until EPA drinking water standards are met.

References 4 and 35, as well as applicable federal, state or local regulations, should be consulted for detailed procedures on ground water monitoring.

4.9 AIR EMISSION CONTROL

During the operation and closure of SI's for hazardous material, emissions of gases and particulate matter may be minimized or eliminated by properly engineered operations. Detailed technical criteria for controlling emissions are presented in the following subsections.

4.9.1 Organic Gas Emission Reduction Procedures

Section 3.7 presented considerations for closure plans for impoundment sites that would minimize the emission of organic gases. This section discusses the control mechanisms available for gas emissions.

Surface drying beds and infiltration lagoons constitute the largest segment of SI's, and these units have been widely used for the economical dewatering of slurries and sludges. The practice of impoundment sludge drying has decreased for large publicly owned treatment works but continues for large industrial plants, especially for process (nonwastewater treatment) sludges. Uncontrollable factors such as rainfall, temperature, drainage rates, and gas (odorous) emissions have caused a decrease in the practice. Dewatering of nonreactive (neither biologically nor chemically) slurries is quite widespread and is not a significant source of gas emissions. Volatilization of materials is dependent on surface exposure and the characteristics of any cover the vapors may have to pass through.

Recognizing that the closure of operating sites, both new and long-used, may produce gas emissions as varied as the impoundment content constituents, controls under the following list of conditions are described:

- Impoundment loading discontinuation and site consolidation
- Emission control during removal for offsite treatment
- Emission control during open in situ stabilization
- Emission control after site covering

Impoundment Load Discontinuation

Upon discontinuation of impoundment loading, gas emissions can be affected by the dewatering (or aging) of impoundment contents by both surface phenomenon and biochemical activity. The preclosure site survey should inventory impounded waste contents and sample liquids or sludge contents, bottom residue, and underlying soil. Although this survey will be conducted primarily for hazardous waste components, it should include sufficient analysis to determine potential fume or gas generation by direct vaporization, sublimation, or biological degradation.

Mechanisms of explosive and toxic gas emissions from covered impoundments are similar to landfill gas transport mechanisms. Conversely, the mechanism by which directly exposed surfaces of impounded liquids and sludges emit vapors and gases depends on properties of the liquids and gases themselves, not on properties of a cover or surrounding soil.

While impoundments remain open, liquid wastes will continue to emit available organic compounds (benzene, chloroform, chlorinated ethylenes) depending on vapor pressure and exposed surface exchange rate. Temperature and wind (or other mixing sources) increases will accelerate emission rates. Upon consolidation, sludges that have a decreased movement of compounds to the exposed surfaces will exhibit reduced vaporization but increased sublimation. Control of surface emissions can best be accomplished by temporary impoundment covers. Aluminum, glass, and synthetic fiber materials have all been used for impoundment control either to prevent the loss of heat, rainwater input, or gas. Such covers frequently are equipped with vents or exhaust gas treatment facilities. Both supported fixed covers and floating materials are available. The latter type of covers include liquids, foams, absorbant beads, and thin synthetic extruded products. Costs for these controls as well as their handling and disposal must be considered.

In a laboratory study of the volatilization of hexachlorobenzene, waste covered with various layers of material had the following flux rates:

Cover	HCB vapor flux (kg/hectare/year)
None	317
1.9 cm topsoil	4.56
0.15 mm polyethylene film	201
1.43 cm water	0.38
120 cm topsoil (silty clay loam)	0.066

The flux rates through soil were not attained readily as the soil adsorbed a considerable amount of HCB. For the 1.9 cm soil, the maximum asmytotic flux rate was attained at 50 days, while the 120 cm soil cover would have required several years to reach a stable flux.[36] Comparison of flux values for the no cover and 120 cm topsoil conditions indicate excellent control of emitted HCB from the waste material. This excellent vapor control is improved further by increased soil compaction. The relative flux rates given above are also typical of other compounds. Thus, the comparative control is indicative of efficiency for other compounds as well.

Bacterial activity and algae growth on organic sludges and liquid wastes can continue to produce gases during stabilization. Biologically generated gas emission rates will decrease upon sludge consolidation. Control of emissions from impoundments during exposed stabilization can be effected by stripping existing gases in liquids through mixing and pH change. Biological and chemical production of gases can be limited by rapid dewatering (employing absorbants -- soil, cement, crushed coral, or draining) or chemically fixing the waste.

Emission Controls During Removal for Offsite Treatment

Control of air emissions during the removal of accumulated impoundment material may be necessary. Reduced sulfurous gases from processing wastes or organic material decomposition can be emitted at unacceptable levels during liquid or semisolid material removal. Likewise, losses of solvents may be excessive during these operations. The following emission containment systems use commercially available equipment and materials:

- Pressurized liquid pumping withdrawal and disposal (gases remain entrained)
- Solidification and removal (employing fixation or water sorbtion)
- Gas adsorption, containment, or biological transformation (using chemicals or barriers)
- Gas or vapor purging and residue removal (purging under pressure or unpressurized)

As described above, a preclosure site survey should provide an inventory of impoundment conditions that would indicate the probability of gas generation. Control is most frequently accomplished to ensure worker safety or surrounding environmental aesthetics.

Open stabilization of contents may be the most feasible closure operation for an impoundment except for safety and air considerations. A plan that covers such an operation should document the characterization of the site (primarily through content inventory and sampling survey) and identify probable air emissions. Emissions abatement procedures identified in the previous sections are applicable to in situ stabilization.

Emission Control After Site Closure and Covering

Several devices are used to control gas emissions after impoundment covering. However, proper cover construction after waste stabilization is a preferred control of such emissions. Consideration of gas generation and control is an integral part of site rehabilitation and greatly influences post-closure uses. The listing of incompatible waste groups (Federal Register, Vol. 43, No. 243, December 18, 1978) is an initial source listing possible gas generating reactions for various groups of impoundment materials and consolidating materials. By adding content inventories and sampling surveys, the impoundment content characterization should be complete and provide the basis for determination of air emission control needs

Common gas control devices used in landfills consist of trenches, piping vents, and barriers. Trenches may be cut continuously around the reclaimed deposit and backfilled with gravel. Such a trench will vent gases produced within the deposit area. Surface areas must have a more impervious cover of saturated clay, artificial cover liner, or similar material. Piping vents are usually constructed similarly to trenches but are placed at intervals around a deposit area. Frequently the pipes are pumped out if used on high organic content landfill areas.

To exclude gas, movement barriers are constructed of compacted clay or other impervious liner material. Often such liners are placed in trenches or as barrier walls underground. These operate in a similar manner to covers except that gas accumulations are not expected to cause ballooning and rupture due to gas entrapment. Placement of saturated cover soils or artificial cover liners are useful for closed impoundment sites as they are for landfills. A rather thorough discussion of such barriers is given in references 1, 37, and 38. The major gas control function of impervious covers is to keep those gases within the closed impoundment site below the surface. By keeping the gases submerged, three mechanisms will dilute their environmental effect:

- Gases that diffuse laterally out beyond the surface cover will be distributed across a wider area and physically diluted
- Gases entrapped will undergo readsorption and chemical degradation by soil components and microorganisms
- Gases that encounter moving ground water will be moved to areas where they are vented or acted on by soil organisms

Surface barriers can effectively control direct vaporization and sublimation. Biologically or chemically generated gases diffuse up through any more permeable vent in the cover barrier. Such unplanned venting can occur through drying cracks in clay, breaks in the cover (poor seals or ruptures in artifical liners), or discontinuities in the barrier, such as rock outcroppings in clay, incomplete compaction on various layers or abandoned well vents as described previously.

A special case of application of surface cover material to impoundments occurs for material addition to liquid or sludge contents for enhanced consolidation or dewatering. Although these practices (fixation, absorption, or material addition) are effective consolidating techniques, they do not necessarily eliminate gases. Consideration should be given for delayed release of gases associated with liquid waste consolidation or possible generation of flammable or toxic gases.

4.9.2 Fugitive Dust Abatement

As discussed in Section 3.7, fugitive dust emissions may be generated during closure and post-closure use of SI's. These emissions are generated primarily from wind erosion of open areas, vehicle traffic on unpaved haul roads, and excavation activities. Several options are available during closure and post-closure use of impoundments for reducing the potential for dust generation.

Excavation Activities

Wetting and stabilizing are the common control techniques employed in preventing and/or reducing fugitive dust emissions from excavating activities. The effectiveness of these techniques are highly variable because of the site specific characteristics of the emission sources. Generally, surface impounded waste materials would posses sufficient moisture so that wetting or application of soil stabilizers for dust abatement would be infrequently required.

Unpaved Haul Roads

Fugitive dust emissions from unpaved haul roads can be reduced or eliminated by using wet suppression, stabilization, or speed reduction techniques. Wet suppression is a farily inexpensive short-term method of controlling dust that can be used on a confined site. Dust emissions reductions of 50 percent have been reported by wetting haul roads twice per day with an application of 2 liters of water per square meter.[40]

Stabilization methods that isolate the dust sources from the traffic disturbances can be used on haul roads. This can be done physically by adding a layer of material on the exposed surfaces or chemically by using materials that help to bind the dust to larger surface particles. Gravel added to the haul road surface is used as a physical stabilizer. In a study comparing various methods of controlling emission from unpaved roads in Arizona, gravel paving had an annual control efficiency of 50 percent and a cost effectiveness of $12/Mg of dust, while chip seal paving had air effectiveness of 100 percent and a cost effectiveness of $11.9/Mg.[39] Chemical stabilization involves the use of binding materials that cause dust particles to adhere to larger surface particles. The effectiveness of this method of dust supression on unpaved haul roads is extremely variable primarily depending upon the amount of traffic. Long-term effectiveness of various stabilization chemicals is also quite variable since it is related to the amount of traffic, soil type, and meteorological conditions. A recent study of various chemical stabilizers was made for dust control on unpaved roads and is summarized in reference 39.

Speed reduction of vehicles traveling over unpaved haul roads has been shown to reduce dust emissions because of diminished stirring effects. Reductions of 62 percent can be achieved by lowering the average speed from 56 km/hr to 32 km/hr.[40]

Open Surfaces

Dust emissions caused by wind erosion of surface impounded waste materials or soils covering an SI can be minimized by use of physical, chemical, or vegetative stabilization. Physical stabilization methods function to cover the exposed surfaces with a material that prevents the wind from disturbing the surface particles. Common stabilizer materials include, rock, soil, crushed or granulated slag, bark, and wood chips. The control efficiency of this technqiue depends on the type of material and the type of stabilizer. The primary drawback to physical covers is the high cost involved in their application, particularly when the cover materials are unavailable in the immediate area.

Chemical stabilizers can be added to cover soils to reduce wind erosion. Many types are available and are applied in conjunction with water or separately. A listing of chemical soil stabilizing materials and their recognized attributes are listed in references 41 and 42. Many of the compounds are proprietary developments, and their properties are difficult to evaluate without actual site-specific field testing. In selecting a soil additive, one should consider effectiveness, stability, ease of application, cost, safety, and environmental impact. Most chemical stabilizers only provide dust suppression for a limited period of time, generally no more than a few months; thereafter, a more permanent solution is needed. This solution generally consists of the establishment of a vegetative cover.

Vegetation can be effectively used to stabilize a variety of exposed soil surfaces. This method of stabilization not only provides permanent dust suppression but makes the site more aesthetically acceptable. The control efficiency of this method varies considerably with the amount and type of cover established on the site. Control efficiencies of 50 to 80 percent have been reported.[40] Efficiencies of nearly 100 percent should be achieved with complete vegetative covering on some sites.

Before an effective vegetative stabilization cover can be developed, many of the cover soils must be prepared by the addition of fertilizers, organic matter, pH neutralizers, and the establishment of proper slope and drainage. The selection of the vegetative species to be planted should receive adequate consideration. Plants compatible with the soil type, growing conditions, climatic zone, and site end use should be chosen. In addition, the selected species must be insensitive to gas contamination of their root systems by decompositional gases that may be present in the closed site. References 43 and 44 should be consulted for listings of candidate species and planting techniques.

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